



北京·中國地質大學

China University of Geosciences

艰苦朴素 求真务实
温家宝

铁同位素示踪地球系统氧循环 原理与实例

何永胜

第三届非传统稳定同位素地球化学暑期学校

2020.08.13

报告内容

- 铁同位素体系简介
- 分析技术简介
- 浅表氧循环示踪
- 深部氧循环示踪

(原理-实例)

一、铁同位素体系简介

铁(Fe)元素

第八族

原子序数: 26

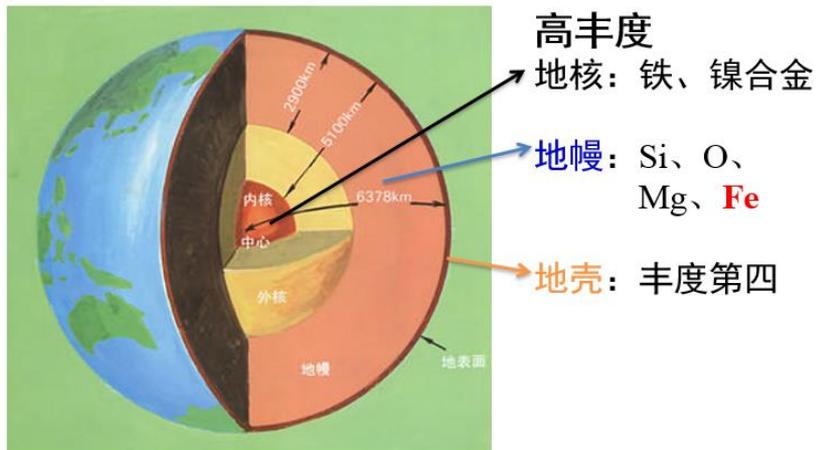
质量数: 56

Periodic Table Of Elements

										0																									
										He Helium 1s ² 4.003																									
IA												IIA		IIIA		IVA		VA		VIA		VIIA		VIIIA											
1												2		3		4		5		6		7		8											
H Hydrogen 1s ¹ 1.0079												Li Lithium 2s ¹ 6.941		Be Beryllium 2s ² 9.012		B Boron 2s ² 2p ¹ 10.81		C Carbon 2s ² 2p ² 12.01		N Nitrogen 2s ² 2p ³ 14.01		O Oxygen 2s ² 2p ⁴ 16.00		F Fluorine 2s ² 2p ⁵ 18.99		Ne Neon 2s ² 2p ⁶ 20.18									
3												4		5		6		7		8		9		10											
Na Sodium 3s ¹ 22.99												Mg Magnesium 3s ² 24.31		Al Aluminum 3s ² 3p ¹ 26.98		Si Silicon 3s ² 3p ² 28.09		P Phosphorus 3s ² 3p ³ 30.97		S Sulfur 3s ² 3p ⁴ 32.07		Cl Chlorine 3s ² 3p ⁵ 34.45		Ar Argon 3s ² 3p ⁶ 39.95											
19		20		21		22		23		24		25		26		27		28		29		30		31		32		33		34		35		36	
K Potassium 4s ¹ 39.10		Ca Calcium 4s ² 40.08		Sc Scandium 3d ¹ 4s ² 44.96		Ti Titanium 3d ² 4s ² 47.87		V Vanadium 3d ³ 4s ² 50.94		Cr Chromium 3d ⁵ 4s ¹ 52.00		Mn Manganese 3d ⁵ 4s ² 54.94		Fe Iron 3d ⁶ 4s ² 55.84		Co Cobalt 3d ⁷ 4s ² 58.93		Ni Nickel 3d ⁸ 4s ² 58.69		Cu Copper 3d ¹⁰ 4s ¹ 63.55		Zn Zinc 3d ¹⁰ 4s ² 65.39		Ga Gallium 4s ² 4p ¹ 69.72		Ge Germanium 4s ² 4p ² 72.61		As Arsenic 4s ² 4p ³ 74.92		Se Selenium 4s ² 4p ⁴ 78.96		Br Bromine 4s ² 4p ⁵ 79.90		Kr Krypton 4s ² 4p ⁶ 83.80	
37		38		39		40		41		42		43		44		45		46		47		48		49		50		51		52		53		54	
Rb Rubidium 5s ¹ 85.47		Sr Strontium 5s ² 87.62		Y Yttrium 4d ¹ 5s ² 88.91		Zr Zirconium 4d ² 5s ² 91.22		Nb Niobium 4d ⁴ 5s ¹ 92.91		Mo Molybdenum 4d ⁵ 5s ¹ 95.94		Tc Technetium 4d ⁵ 5s ² 99		Ru Ruthenium 4d ⁷ 5s ¹ 101.07		Rh Rhodium 4d ⁸ 5s ¹ 102.91		Pd Palladium 4d ¹⁰ 106.42		Ag Silver 4d ¹⁰ 5s ¹ 107.87		Cd Cadmium 4d ¹⁰ 5s ² 112.41		In Indium 5s ² 5p ¹ 114.82		Sn Tin 5s ² 5p ² 118.71		Sb Antimony 5s ² 5p ³ 121.76		Te Tellurium 5s ² 5p ⁴ 127.60		I Iodine 5s ² 5p ⁵ 126.90		Xe Xenon 5s ² 5p ⁶ 131.29	
55		56		57-71		72		73		74		75		76		77		78		79		80		81		82		83		84		85		86	
Cs Cesium 6s ¹ 132.91		Ba Barium 6s ² 137.33		Lanthanides 57-71		Hf Hafnium 5d ² 6s ² 178.49		Ta Tantalum 5d ³ 6s ² 180.91		W Tungsten 5d ⁴ 6s ² 183.84		Re Rhenium 5d ⁵ 6s ² 186.21		Os Osmium 5d ⁶ 6s ² 190.23		Ir Iridium 5d ⁷ 6s ² 192.22		Pt Platinum 5d ⁹ 6s ¹ 195.08		Au Gold 5d ¹⁰ 6s ¹ 196.97		Hg Mercury 5d ¹⁰ 6s ² 200.59		Tl Thallium 6s ² 6p ¹ 204.38		Pb Lead 6s ² 6p ² 207.2		Bi Bismuth 6s ² 6p ³ 208.98		Po Polonium 6s ² 6p ⁴ (209)		At Astatine 6s ² 6p ⁵ (210)		Rn Radon 6s ² 6p ⁶ (222)	
87		88		89-103		104		105		106		107		108		109		110		111		112		113		114		115		116		117		118	
Fr Francium 7s ¹ (223)		Ra Radium 7s ² (226)		Actinides 89-103		Rf Rutherfordium 6d ² 7s ² (263)		Db Dubnium 6d ³ 7s ² (263)		Sg Seaborgium 6d ⁴ 7s ² (266)		Bh Bohrium 6d ⁵ 7s ² (264)		Hs Hassium 6d ⁶ 7s ² (265)		Mt Meitnerium 6d ⁷ 7s ² (268)		Ds Darmstadtium 6d ⁹ 7s ² (268)		Rg Roentgenium 6d ¹⁰ 7s ² (272)		Cn Copernicium 6d ¹⁰ 7s ² (277)		Nh Nihonium 7s ² 7p ¹ (284)		Fl Flerovium 7s ² 7p ² (284)		Mc Moscovium 7s ² 7p ³ (285)		Lv Livermorium 7s ² 7p ⁴ (286)		Ts Tennessine 7s ² 7p ⁵ (287)		Og Oganesson 7s ² 7p ⁶ (288)	
57		58		59		60		61		62		63		64		65		66		67		68		69		70		71		72		73			
La Lanthanum 5d ¹ 6s ² 138.91		Ce Cerium 4f ¹ 5d ¹ 6s ² 140.12		Pr Praseodymium 4f ³ 6s ² 140.91		Nd Neodymium 4f ⁴ 6s ² 144.24		Pm Promethium 4f ⁵ 6s ² (145)		Sm Samarium 4f ⁶ 6s ² 150.36		Eu Europium 4f ⁷ 6s ² 151.96		Gd Gadolinium 4f ⁷ 5d ¹ 6s ² 157.25		Tb Terbium 4f ⁹ 6s ² 158.93		Dy Dysprosium 4f ¹⁰ 6s ² 162.50		Ho Holmium 4f ¹¹ 6s ² 164.93		Er Erbium 4f ¹² 6s ² 167.26		Tm Thulium 4f ¹³ 6s ² 168.93		Yb Ytterbium 4f ¹⁴ 6s ² 173.04		Lu Lutetium 4f ¹⁴ 5d ¹ 6s ² 174.97							
89		90		91		92		93		94		95		96		97		98		99		100		101		102		103		104		105			
Ac Actinium 6d ¹ 7s ² (227)		Th Thorium 6d ² 7s ² 232.04		Pa Protactinium 5f ² 6d ¹ 7s ² 231.04		U Uranium 5f ³ 6d ¹ 7s ² 238.03		Np Neptunium 5f ⁴ 6d ¹ 7s ² 237		Pu Plutonium 5f ⁶ 7s ² (244)		Am Americium 5f ⁷ 7s ² (243)		Cm Curium 5f ⁸ 6d ¹ 7s ² (247)		Bk Berkelium 5f ⁹ 7s ² (247)		Cf Californium 5f ¹⁰ 7s ² (251)		Es Einsteinium 5f ¹¹ 7s ² (252)		Fm Fermium 5f ¹² 7s ² (257)		Md Mendelevium 5f ¹³ 7s ² (258)		No Nobelium 5f ¹⁴ 7s ² (259)		Lr Lawrencium 5f ¹⁴ 6d ¹ 7s ² (262)							

一、铁同位素体系简介

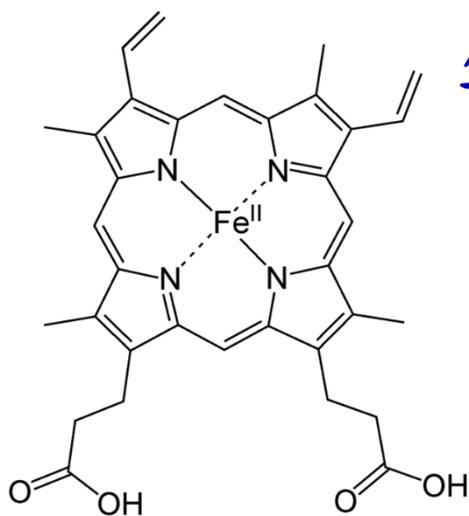
主要元素



变价元素



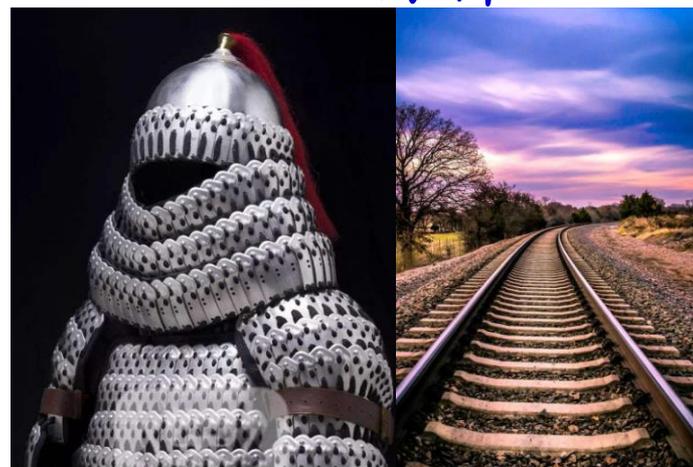
生命元素



血红蛋白

[Wikipedia](#)

工业材料



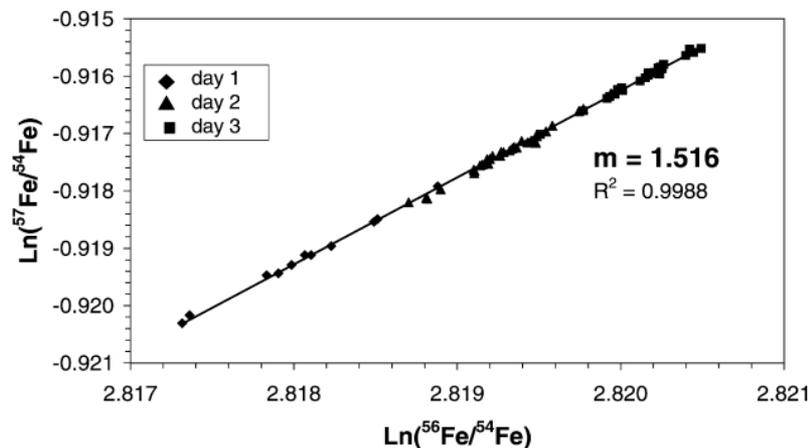
一、铁同位素体系简介

- Fe有四个稳定同位素：

$$\delta^{56}\text{Fe} = \left[\left(\frac{^{56}\text{Fe}}{^{54}\text{Fe}} \right)_{\text{sample}} / \left(\frac{^{56}\text{Fe}}{^{54}\text{Fe}} \right)_{\text{standard}} - 1 \right] \cdot 10^3$$

$$\delta^{57}\text{Fe} = \left[\left(\frac{^{57}\text{Fe}}{^{54}\text{Fe}} \right)_{\text{sample}} / \left(\frac{^{57}\text{Fe}}{^{54}\text{Fe}} \right)_{\text{standard}} - 1 \right] \cdot 10^3$$

Fe	53.93961	5.845	
	55.93494	91.754	
	56.93540	2.1191	
	57.93328	0.2819	



标准：

IRMM-014，欧洲标准局

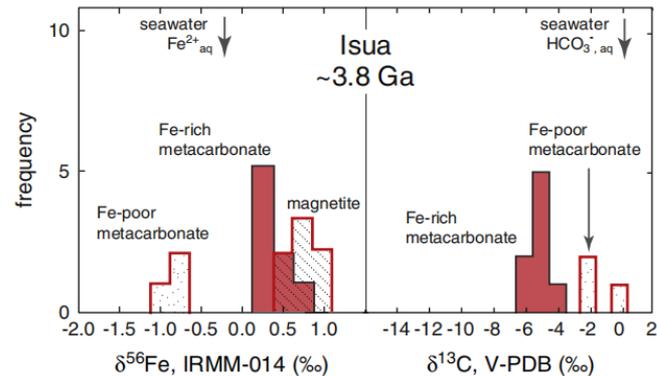
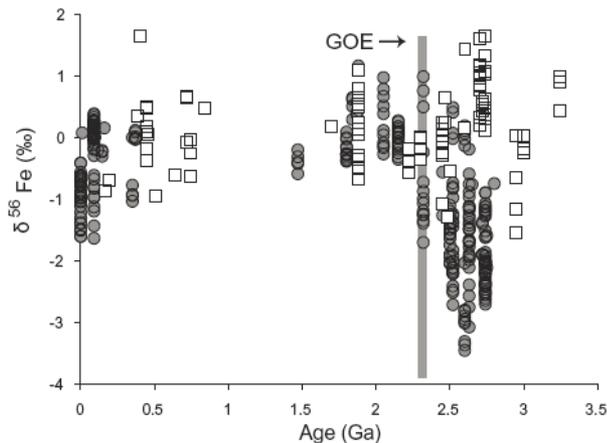
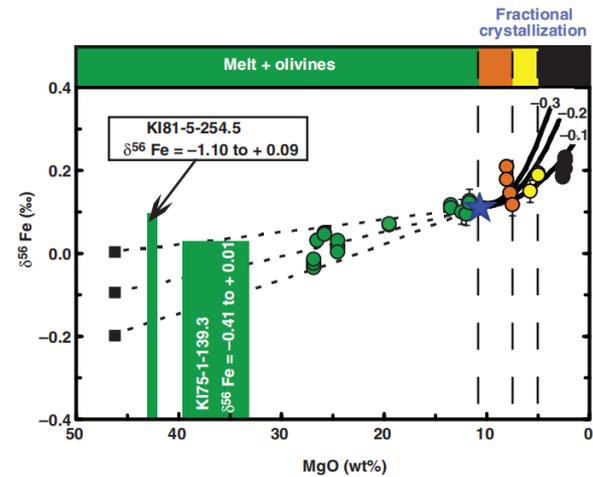
平均火成岩，**Beard et al., 2003**

Average igneous rocks by IRMM-014:
0.09 per mil

Weyer and Schwieters, 2003

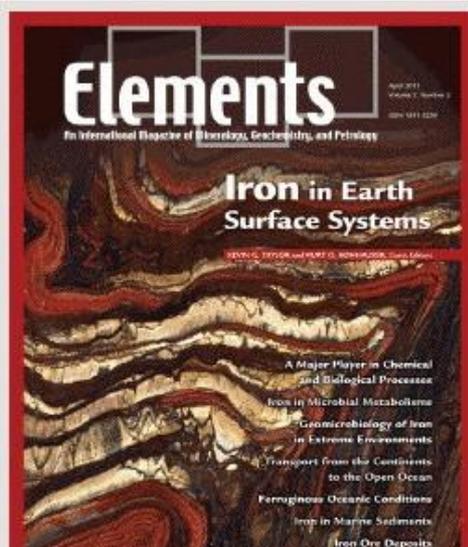
一、铁同位素体系简介

- 在示踪早期行星过程、核幔分异、岩浆演化、矿床成因、生物活动及各种地质体系氧逸度等方面具有巨大潜力



Teng et al., 2008; Poitrasson, 2009; Craddock et al., 2011; Planavsky et al., 2012

一、铁同位素体系简介



April 2011 – Volume 7 Number 2

Iron in Earth Surface Systems

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[Table of contents](#)

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ANRV341-EA36-13 ARI 21 January 2008 20:51



Review in Advance first posted online on February 12, 2008. (Minor changes may still occur before final publication online and in print.)

元素行为

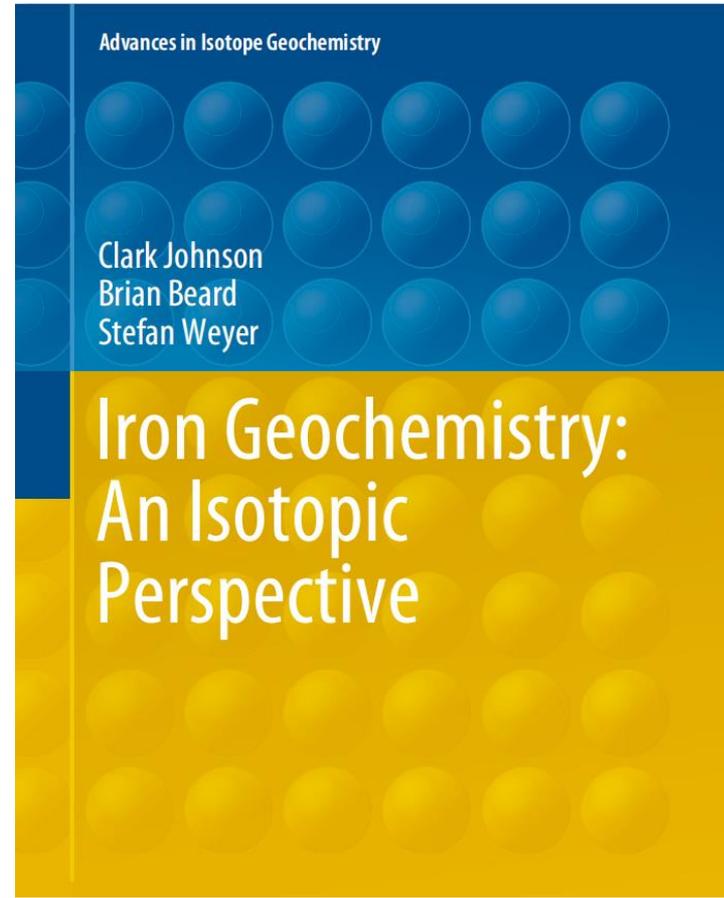
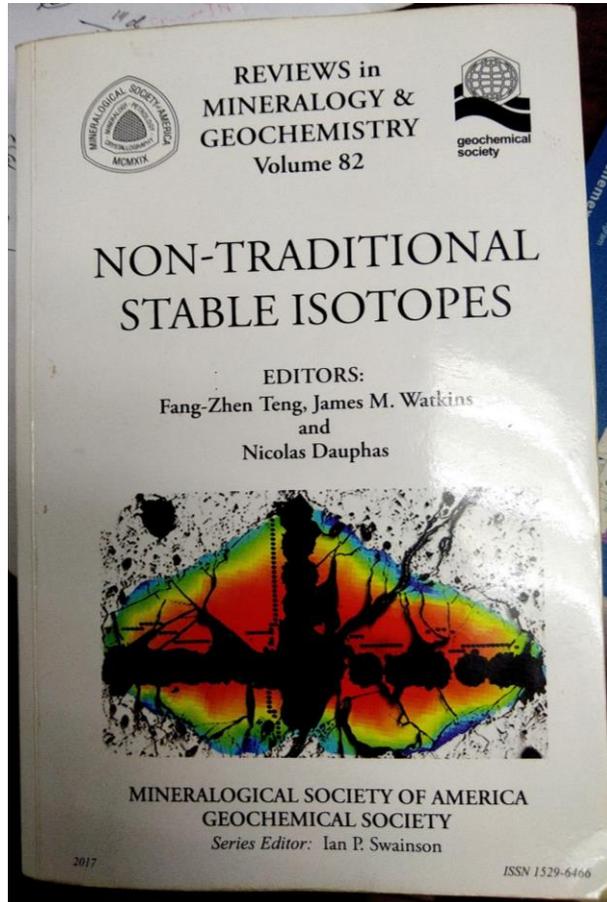
The Redox State of Earth's Mantle

Daniel J. Frost and Catherine A. McCammon

Bayerisches Geoinstitut, University of Bayreuth, Germany;
email: Dan.Frost@uni-bayreuth.de

一、铁同位素体系简介

铁同位素进展



一、铁同位素体系简介

特点

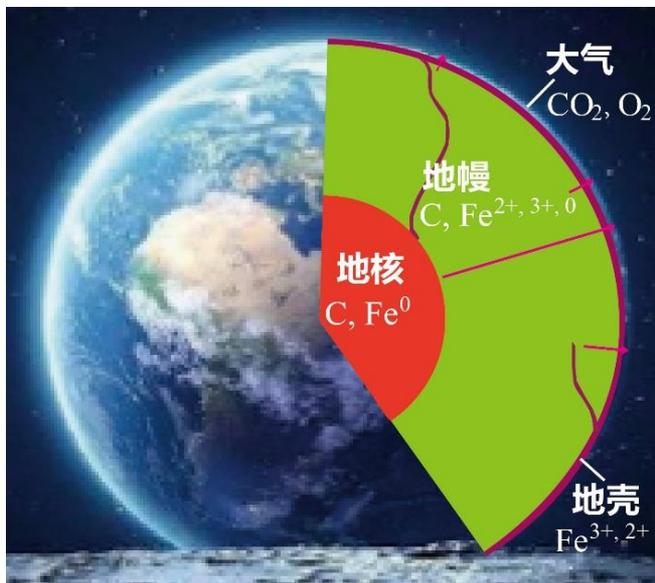
Fe是地球系统主要变价元素



Fe^{3+} 、 Fe^{2+} 、 Fe^0 铁同位素组成不同

示踪
“氧”循环

深部 ← 浅表



现代 → 深时

二、分析技术简介

目标：不产生人为同位素分馏，
或产生的分馏可准确校正

溶样

化学分离

质谱分析

不完全溶样

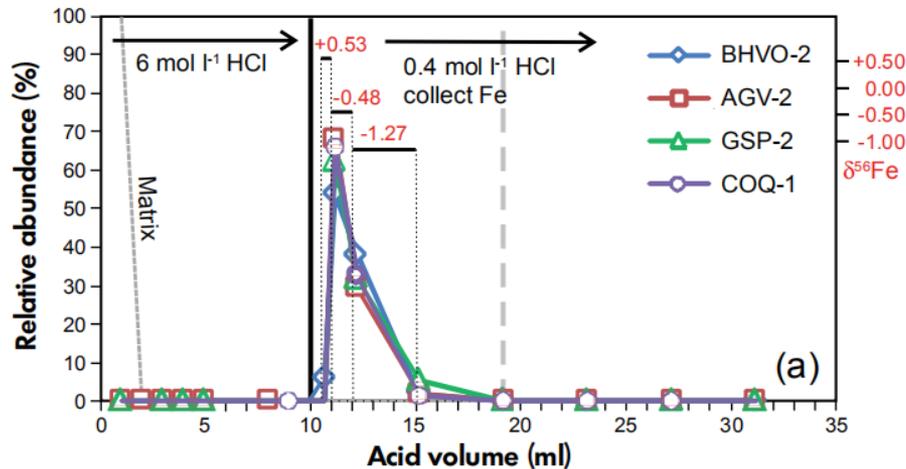
不完全回收

同质异位数
基质效应
质量歧视

全流程本底

二、分析技术简介

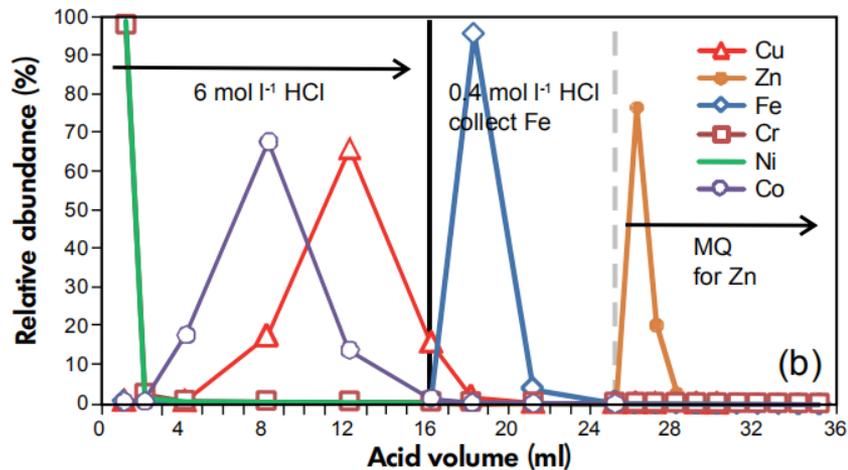
化学流程



溶样 (完全)

AG1X-4, 8, AG-MP-1M等阴离子树脂 (HCl介质, FeCl_4^-)

价态控制、过渡族元素



Strelow, 1980; Zhu et al., 2002; Dauphas et al., 2009; Liu et al., 2014; He et al., 2015 等

二、分析技术简介

分析仪器

热电离质谱仪(双稀释剂)

- 2000年之前；效率低，精度有限[$\delta^{56}\text{Fe} \sim 0.3 \text{ ‰}$]

多道等离子体质谱仪

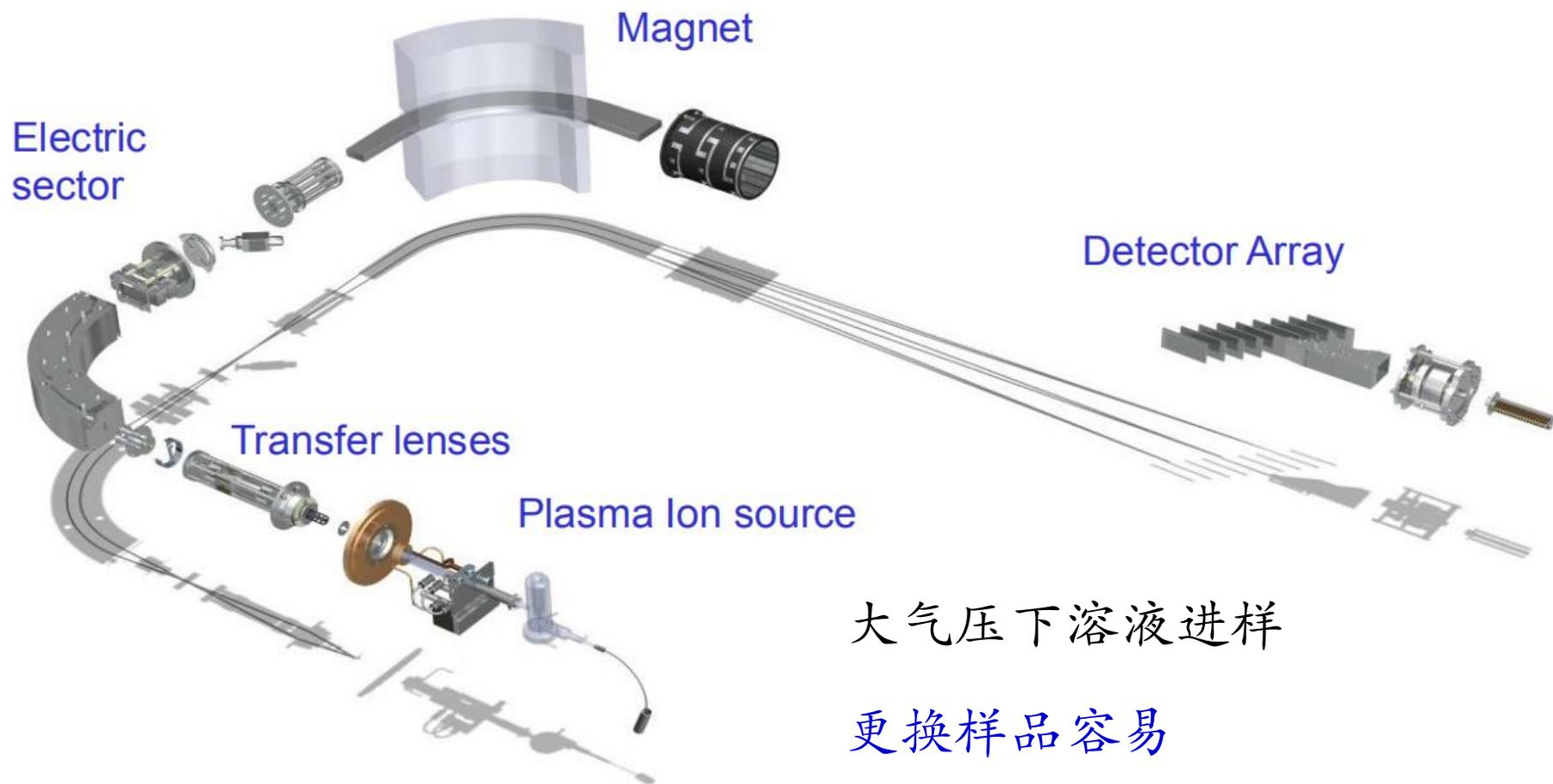
- 2000年之后；效率高，精度高[$\delta^{56}\text{Fe}$ 可优于 0.03 ‰]



*Johnson and Beard, 1999; Belshaw et al., 2000; Dauphas et al., 2009;
He et al., 2015; Chen et al., 2017等*

二、分析技术简介

多道等离子质谱仪



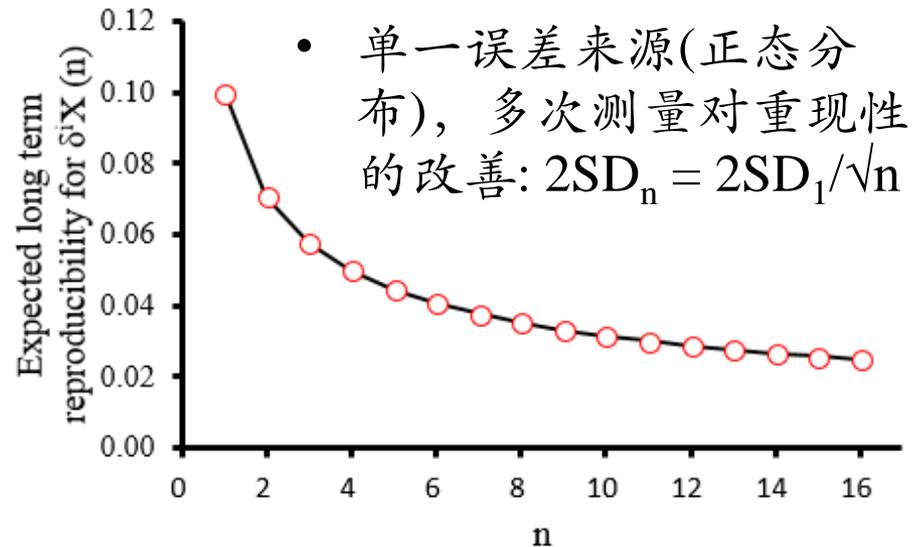
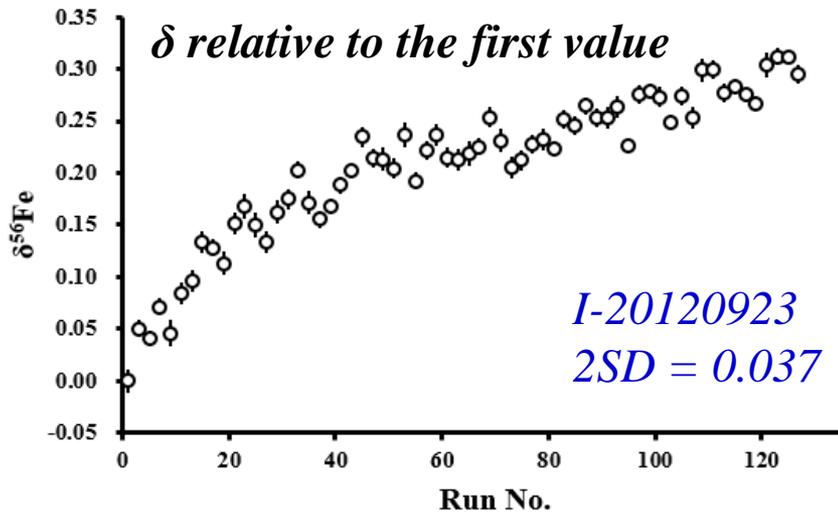
大气压下溶液进样

更换样品容易

测试条件易重复

二、分析技术简介

仪器分馏（质量歧视）校正

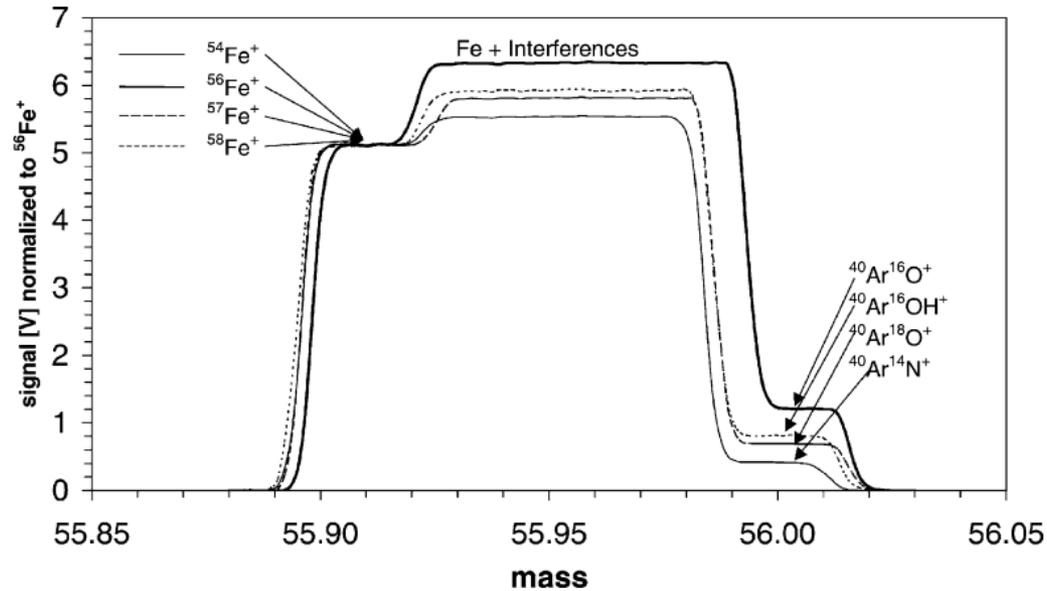


标样-样品间插法(SSB)

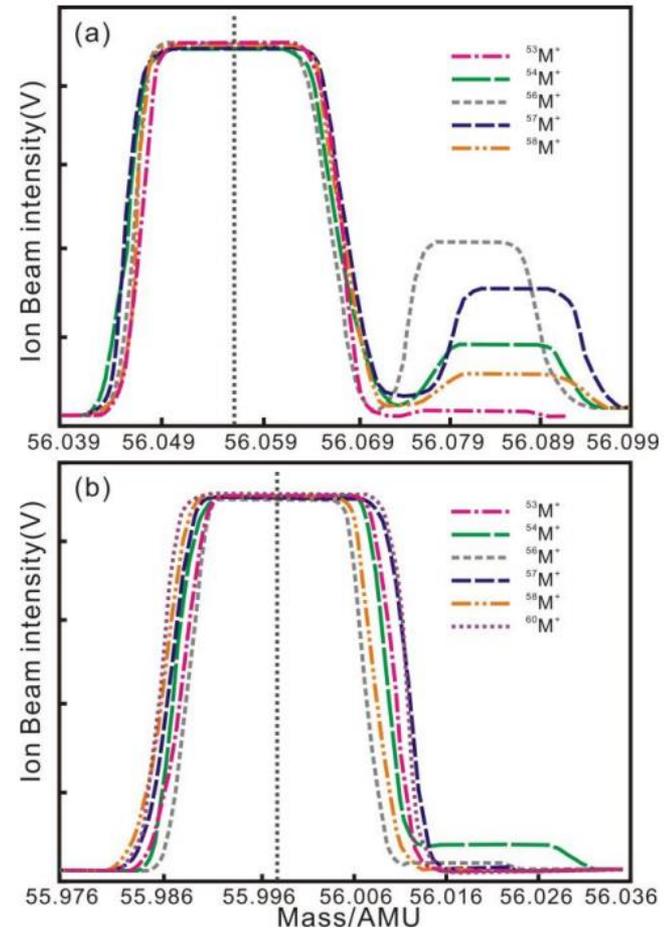
- 标样-样品-标样...-样品-标样
- 假设样品分析时，仪器分馏和间插标样相同（仪器分馏的短时稳定性）
- $\delta^{56}\text{Fe}$ 重现性(2SD)优于0.09‰ ($N=9 \rightarrow 0.03\%$), 优于0.05‰ ($N=4 \rightarrow 0.05\%$)

二、分析技术简介

基团干扰



- 早期：碰撞池、cold plasma
- 当前：高分辨(Neptune, Nu II/III, 大Niu)



Belshaw et al., 2000; Weyer and Schwieters, 2003; Chen et al., 2017

二、分析技术简介

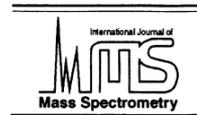
- 成熟方法，国际实验室分析精度（2SD）一般小于0.1‰，通常可优于0.03~0.05 ‰

[中科大、西北大学、地质所、地科院地质所、广化所、地大北京等]



ELSEVIER

International Journal of Mass Spectrometry 197 (2000) 191–195

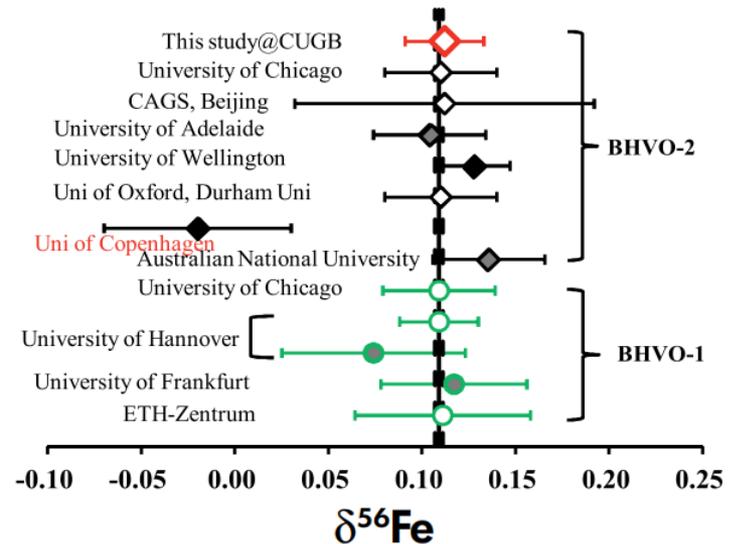


High precision measurement of iron isotopes by plasma source mass spectrometry

N.S. Belshaw, X.K. Zhu, Y. Guo, R.K. O’Nions

Department of Earth Sciences, University of Oxford, Parks Road, Oxford OX1 3PR, UK

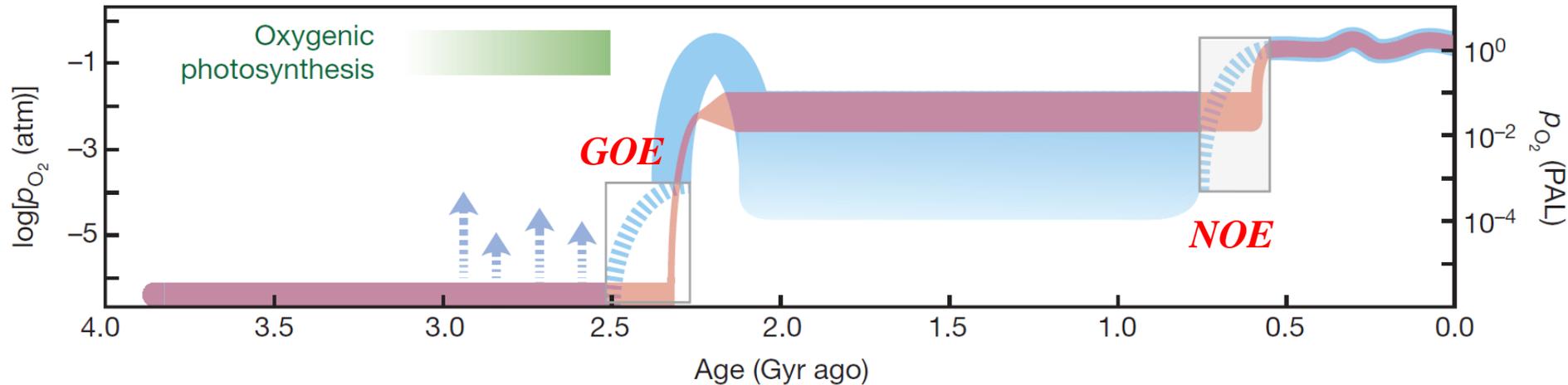
Received 2 July 1999; accepted 15 October 1999



Belshaw et al., 2000; He et al., 2015 等

三、浅表氧循环示踪

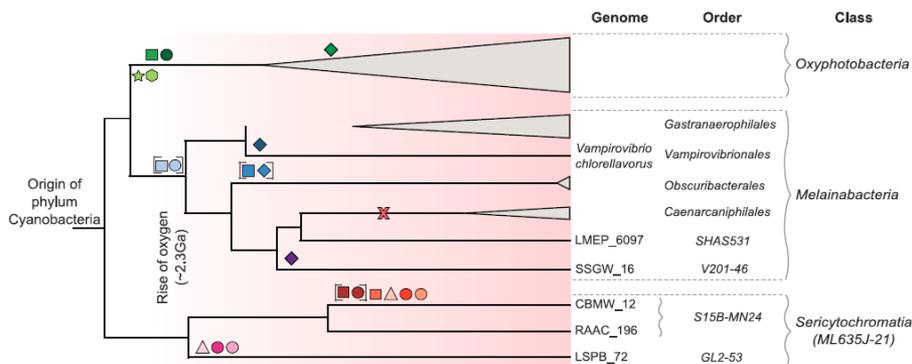
大气氧的演化与动物起源



- 地球早期大气几乎无氧，主要经过两次氧化事件达到当今水平。
- 大气的氧化可能促进了动物的诞生，最终形成了现今的宜居星球。

三、浅表氧循环示踪

• 产氧生物诞生



Soo et al., Science, 2017

• 固体地球(深部过程)

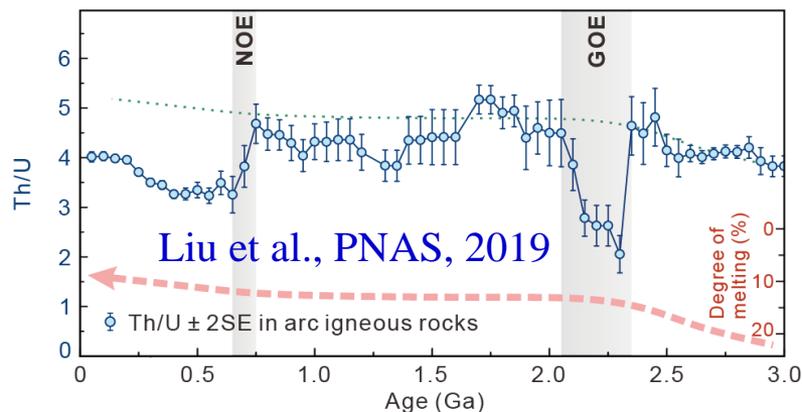
- ✓ 地幔氧逸度演化
- ✓ 铁歧化反应
- ✓ 深部水、碳循环
- ✓ 等

地球系统协同演化

• 固体地球(浅表过程)

- ✓ 地形变化
- ✓ 营养盐输入(如: Ni、P)
- ✓ 风化-蚀变(耗氧通量)
- ✓ 等

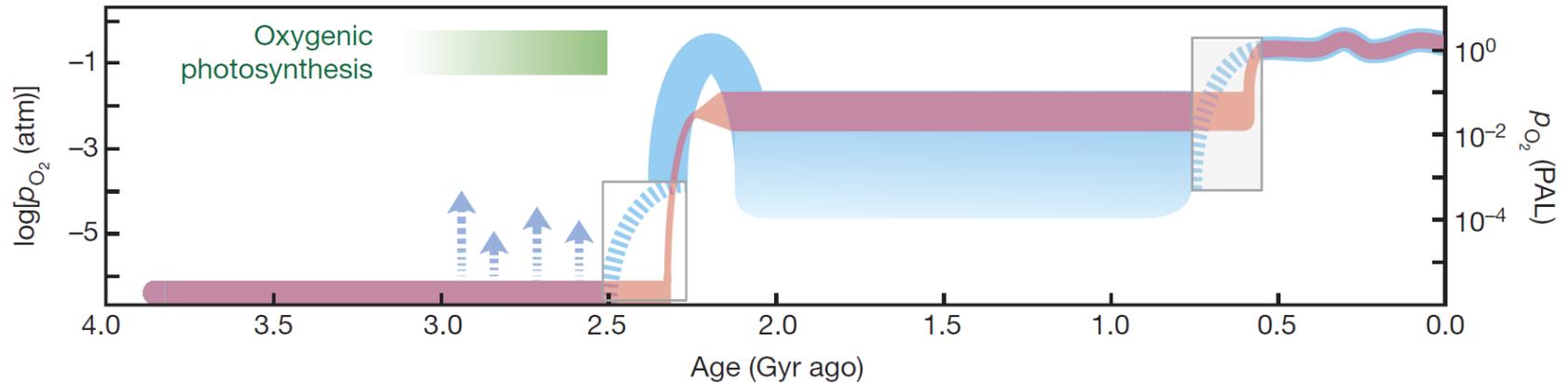
• 固体地球(反馈)



Many other literatures

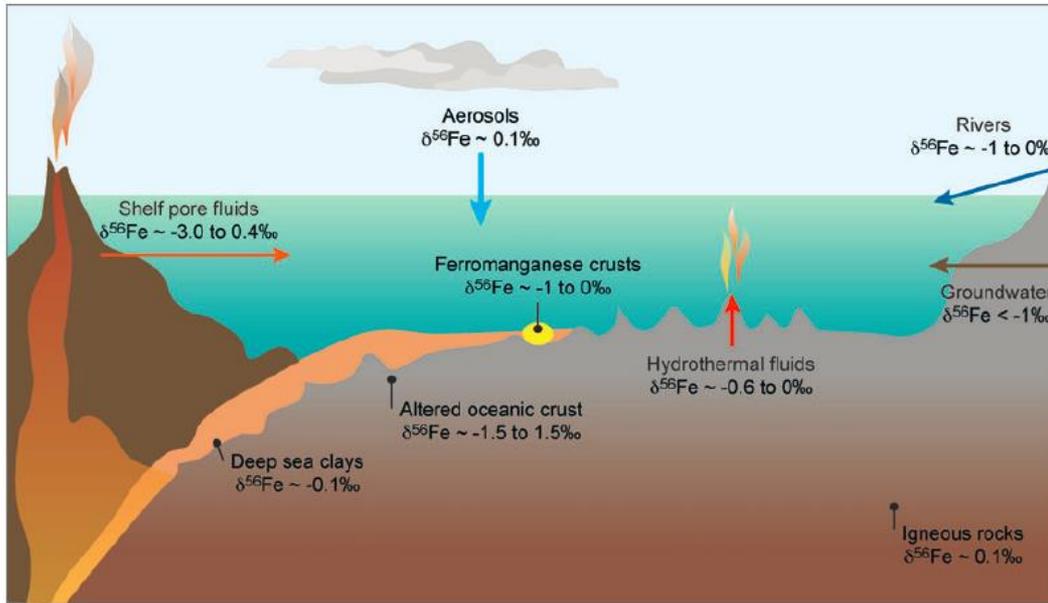
三、浅表氧循环示踪

关键科学问题



- 大气[地球各圈层]“氧”含量如何演化?
- 协同演化的机制是什么?

三、浅表氧循环示踪



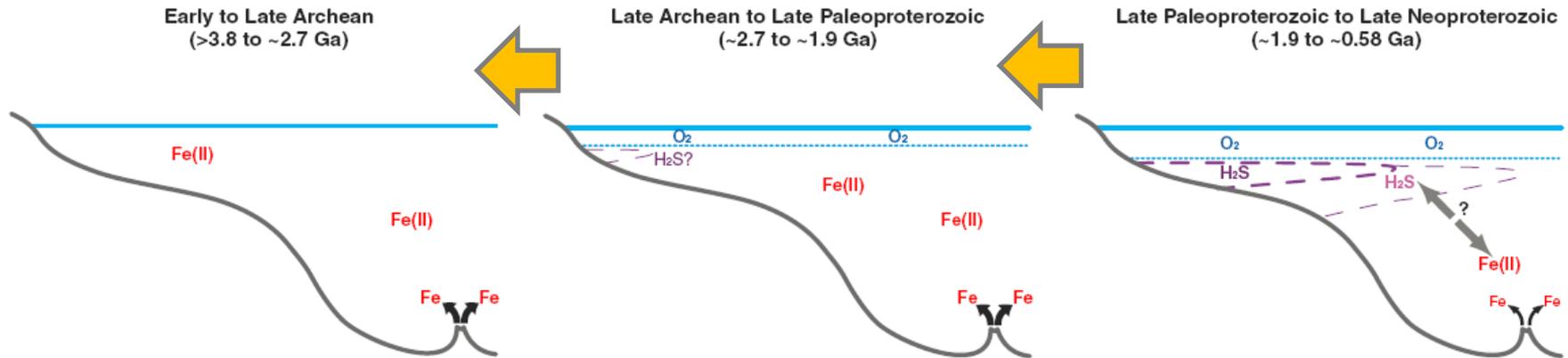
现代开放大洋:

[dFe] ~ 0.05-2 nM

太古代大洋: [dFe] → 0.5 mM

地表Fe循环-氧气含量

[储库、过程、地质记录等]



Anbar et al., 2007; Poulton and Canfield, 2011; Konhauser et al., 2017

三、浅表氧循环示踪

溶解行为

PH=7, 常温, 水溶液为例

- Fe^{3+} :

2.097e-11 g/g, 0.374 nM

现今海水的溶解Fe含量: 0.01~1 nM量级

- Fe^{2+} :

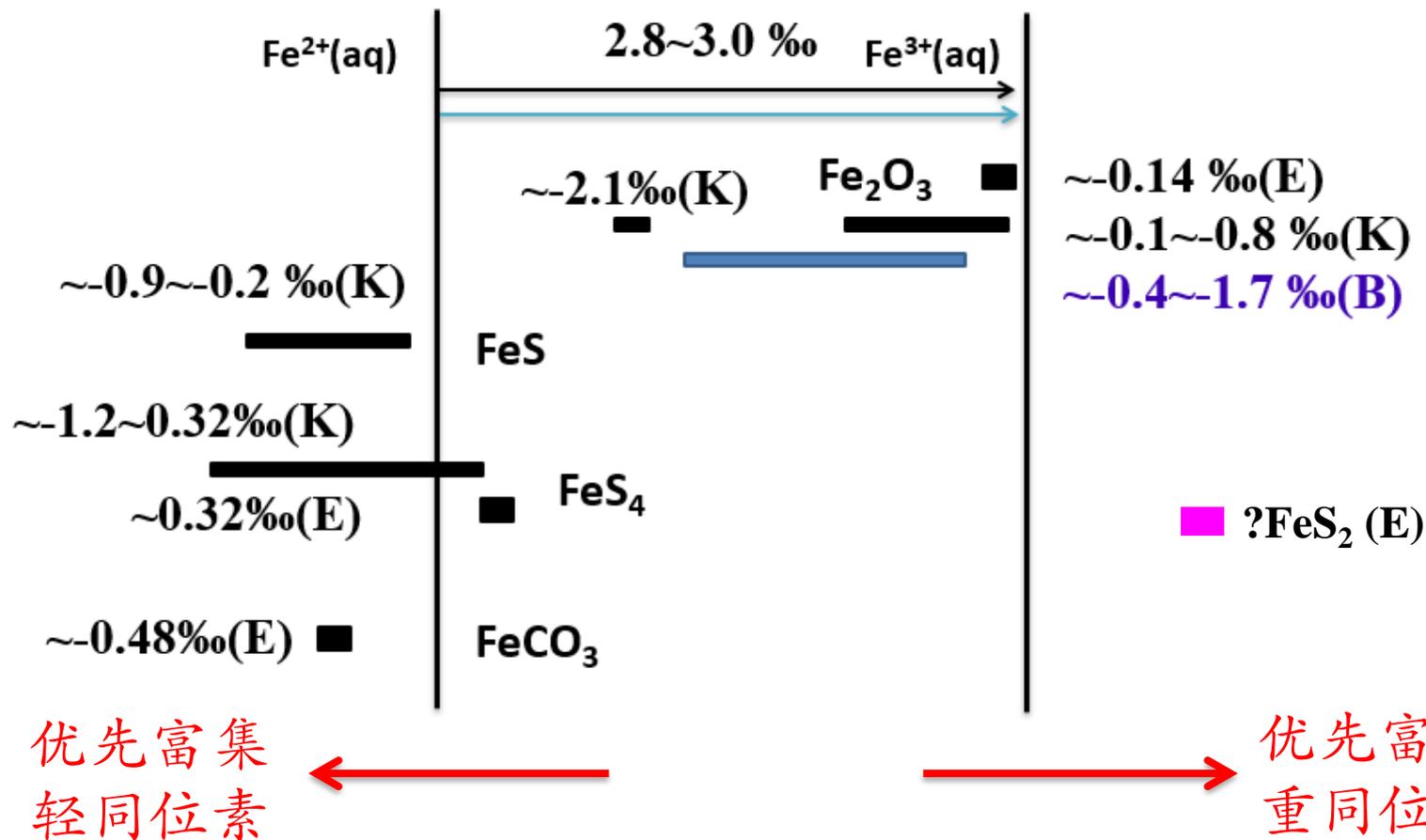
5.26e-7 g/g, 9.38 uM [FeCl_2 , 62.5 g/100 g H_2O]

- FeS_m :

uM级

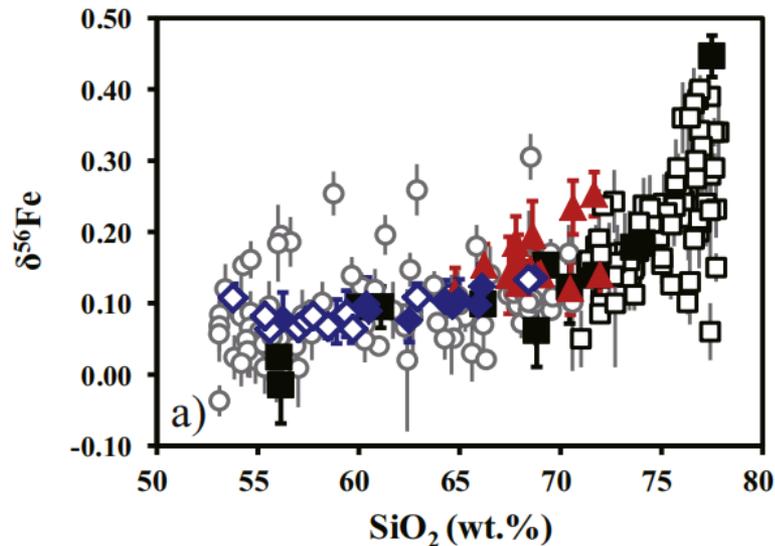
三、浅表氧循环示踪

常见分馏系数



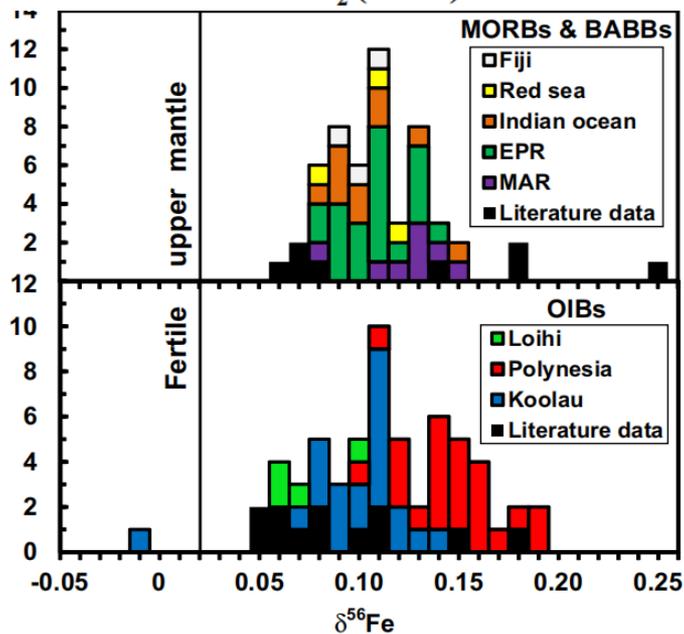
Johnson et al., 2002, 2005; Weltch et al., 2003; Wiesli et al., 2004; Beard and Johnson, 2004; Balci et al., 2006; Dauphas and Rouxel, 2006

三、浅表氧循环示踪



地壳(火成岩基岩)

$\delta^{56}\text{Fe} \sim 0.10\text{‰}$

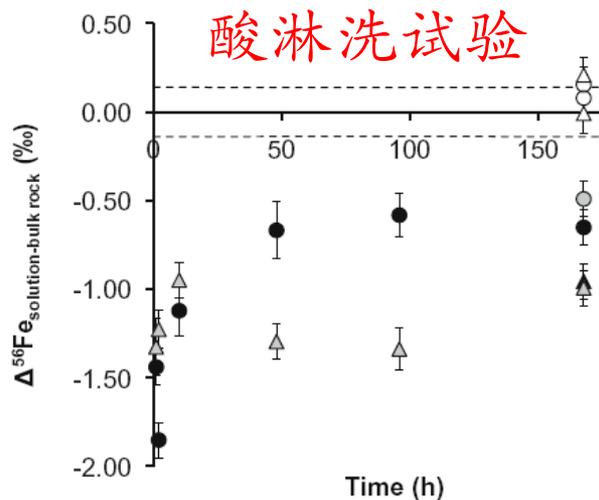


e.g., Poitrasson and Freyrier, 2005; Teng et al., 2013; Foden et al., 2015; He et al., 2017

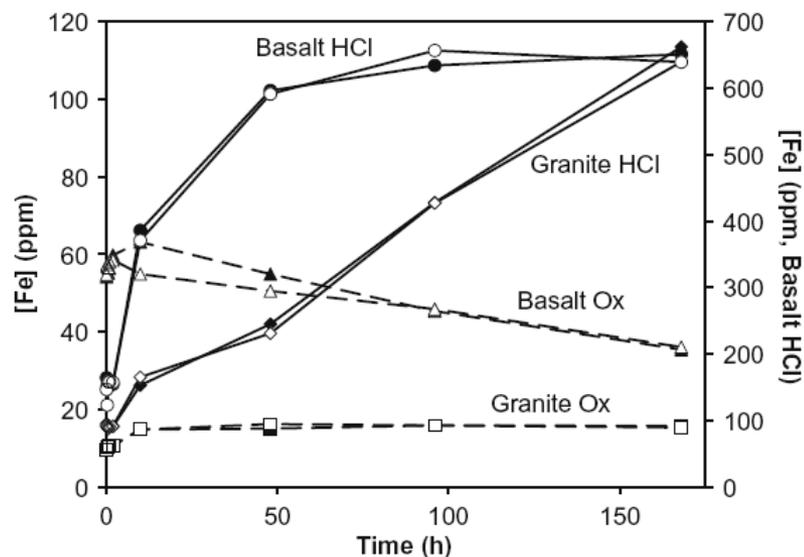
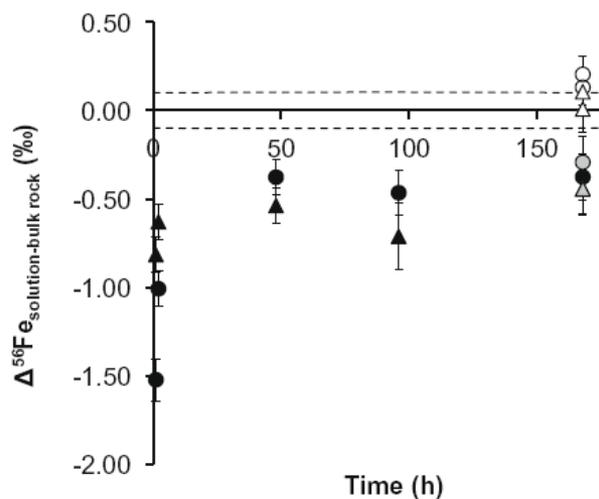
三、浅表氧循环示踪

化学风化

(a) Granite

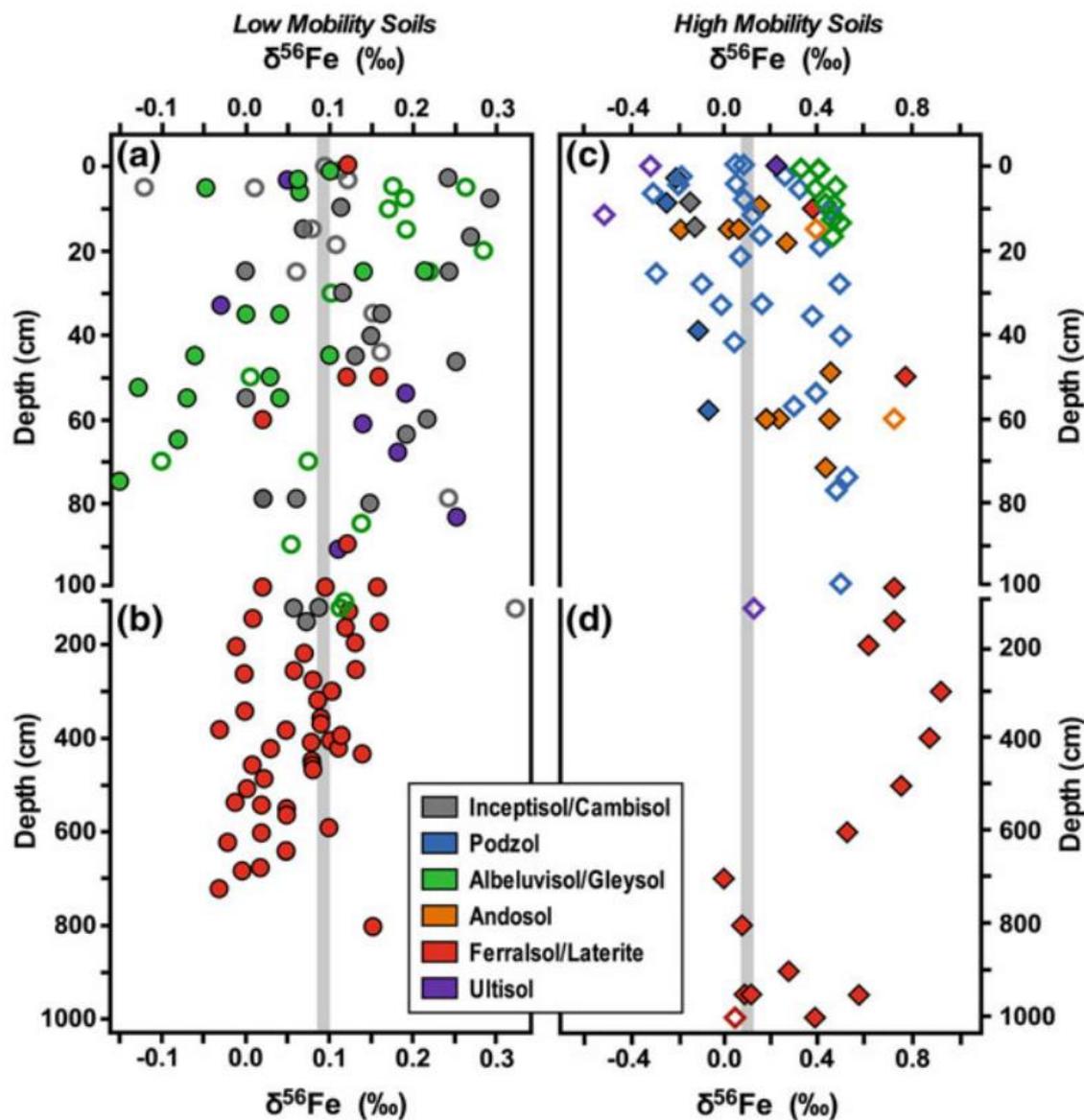


(b) Basalt



- 在硅酸岩风化过程中，**流体一般优先溶解轻Fe同位素**
- 流体洗脱的铁有限，**残留固相同位素组成变化不大**

三、浅表氧循环示踪

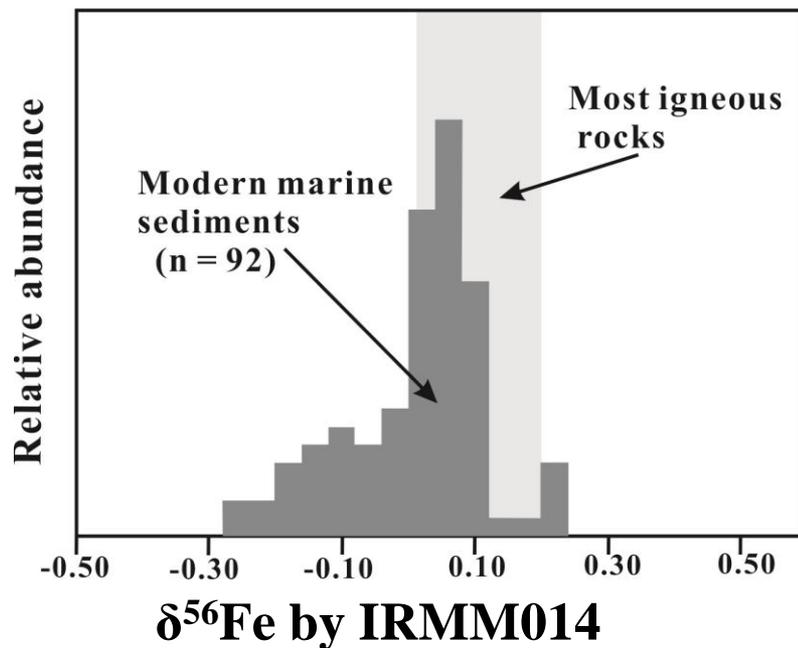
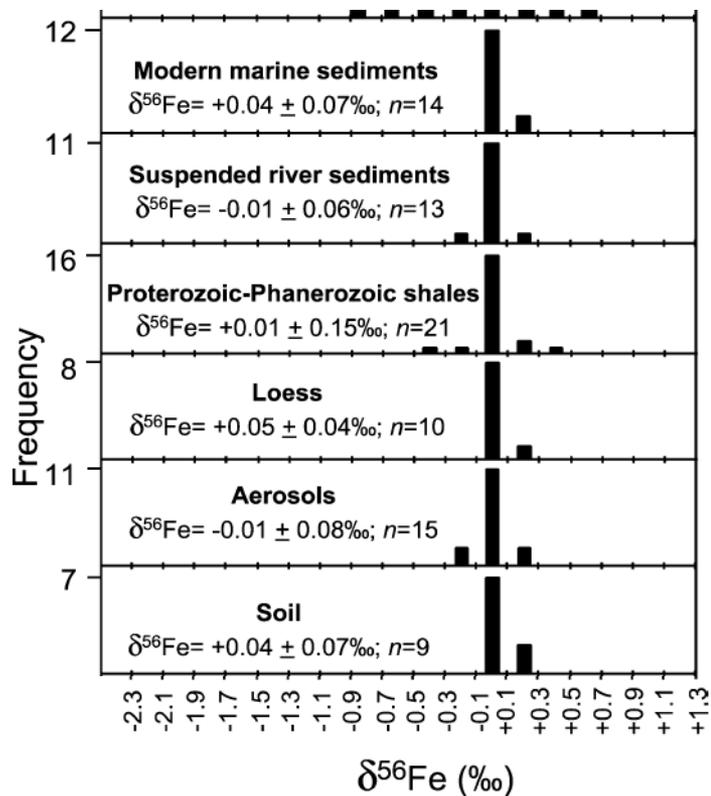


风化剖面

- 和Eh有关
- 在硅酸岩风化过程中，优先丢失轻Fe同位素

三、浅表氧循环示踪

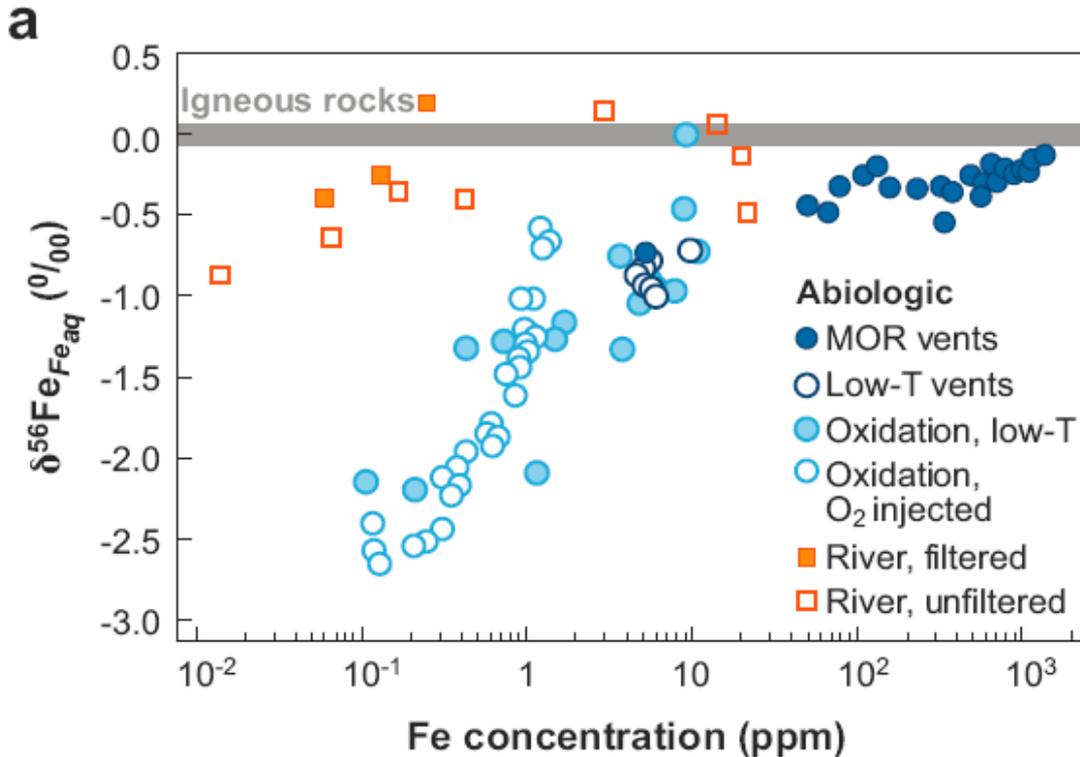
现代海洋沉积物



碎屑沉积物相对火成岩没有发生较大分馏；
总体上，全岩尺度风化残留物的分馏不显著

三、浅表氧循环示踪

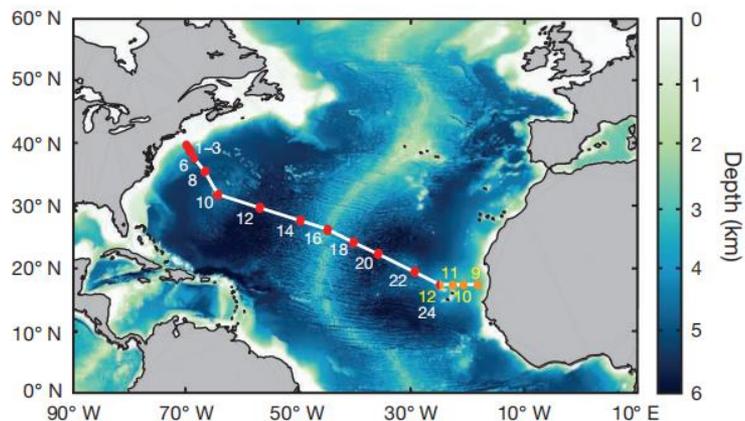
河水、海水、热液、地下水



河流水，海底热液，低温热泉，地下水中溶解铁一般相对偏轻Fe同位素组成

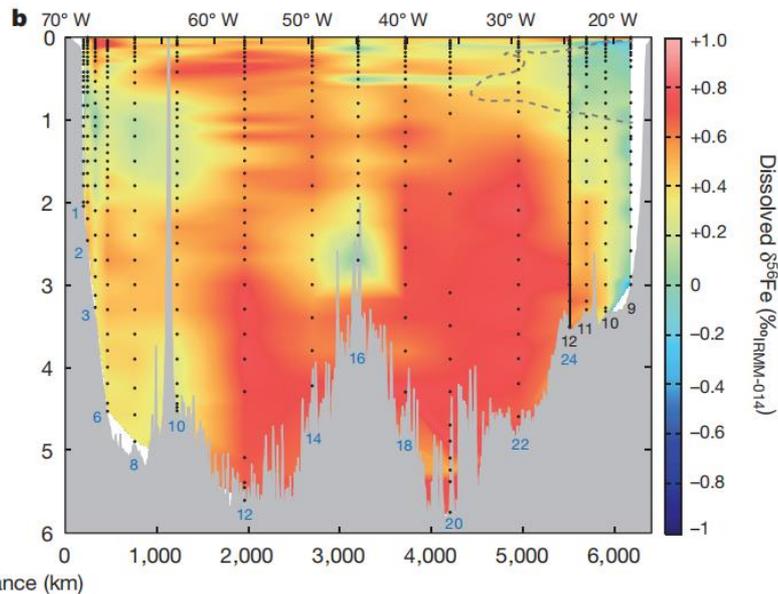
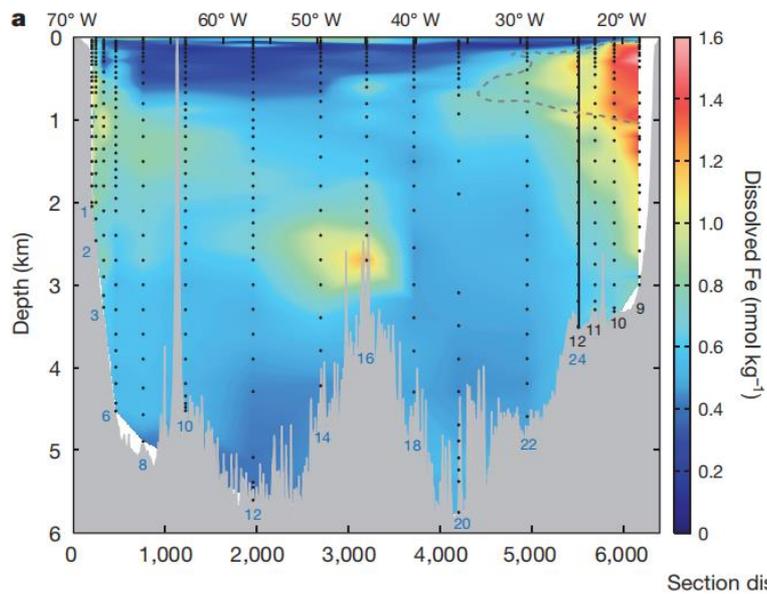
三、浅表氧循环示踪

现代海洋



- 大西洋(GEOTRACES)
- Fe含量和同位素组成不均一
- 大致负相关

Conway and John, 2014



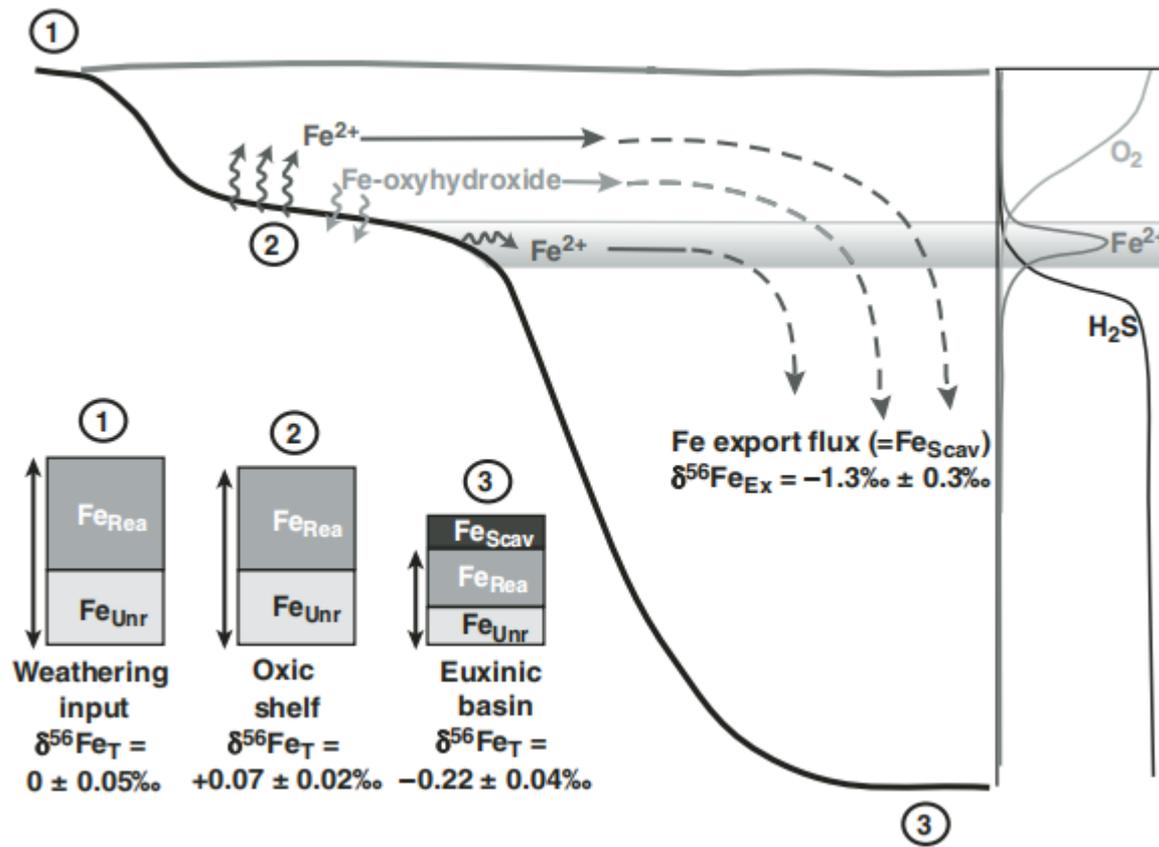
三、浅表氧循环示踪

显生宙碳酸盐

the range of global shales (Beard *et al.* 2003b). Two carbonates (GSR-6 and GSR-13) yielded $\delta^{56}\text{Fe}$ ranging from 0.10 to 0.14‰, also close to igneous rocks and shales. This may suggest that Fe is dominantly present as silica particles in the carbonates, given the very low dissolved Fe content in oxidised Phanerozoic ocean water (Radic *et al.* 2011) and the fact that these carbonates have SiO_2 contents from 6.65 to 15.60% *m/m* (IGGE certificates). Sandstone GSR-4 had a $\delta^{56}\text{Fe}$ value of

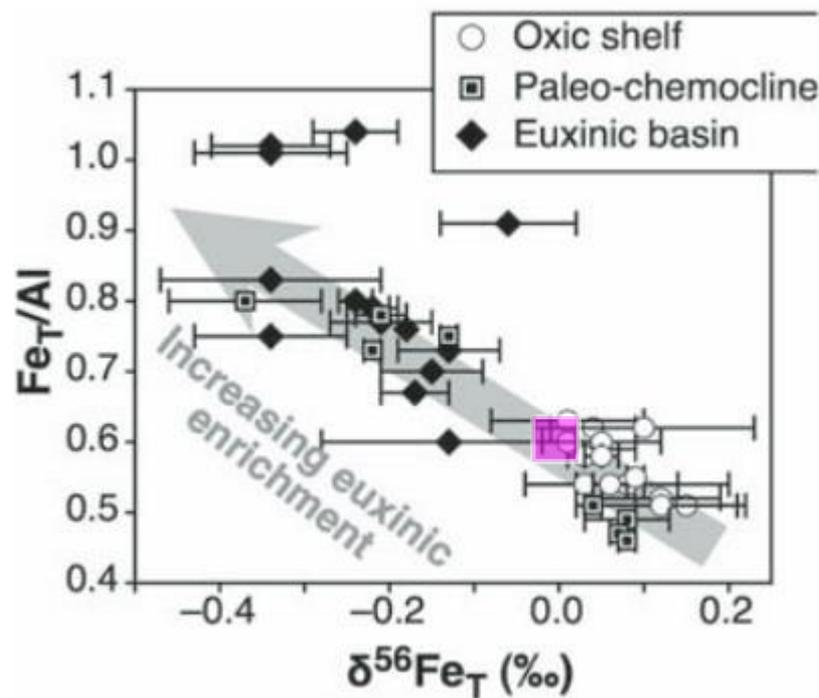
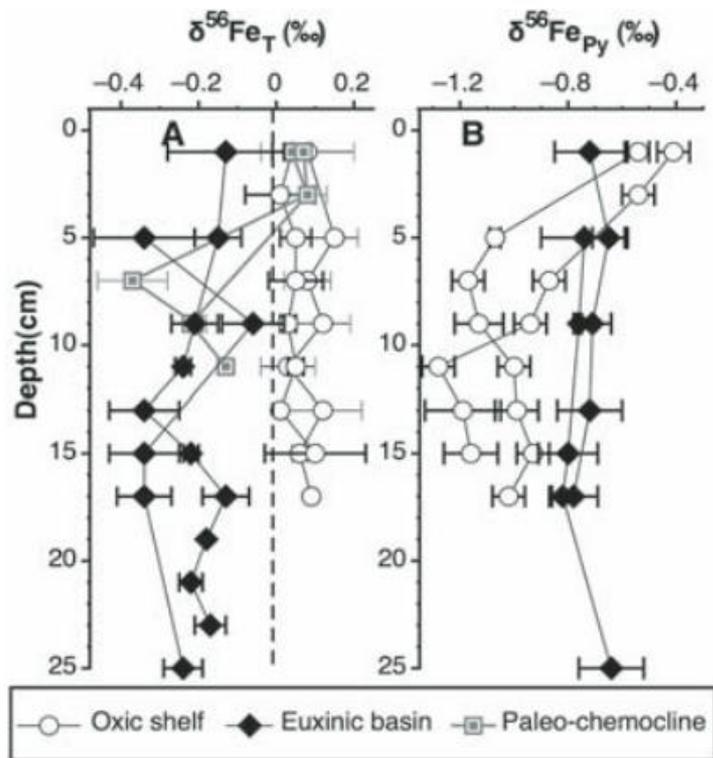
三、浅表氧循环示踪

现代黑海



三、浅表氧循环示踪

现代黑海

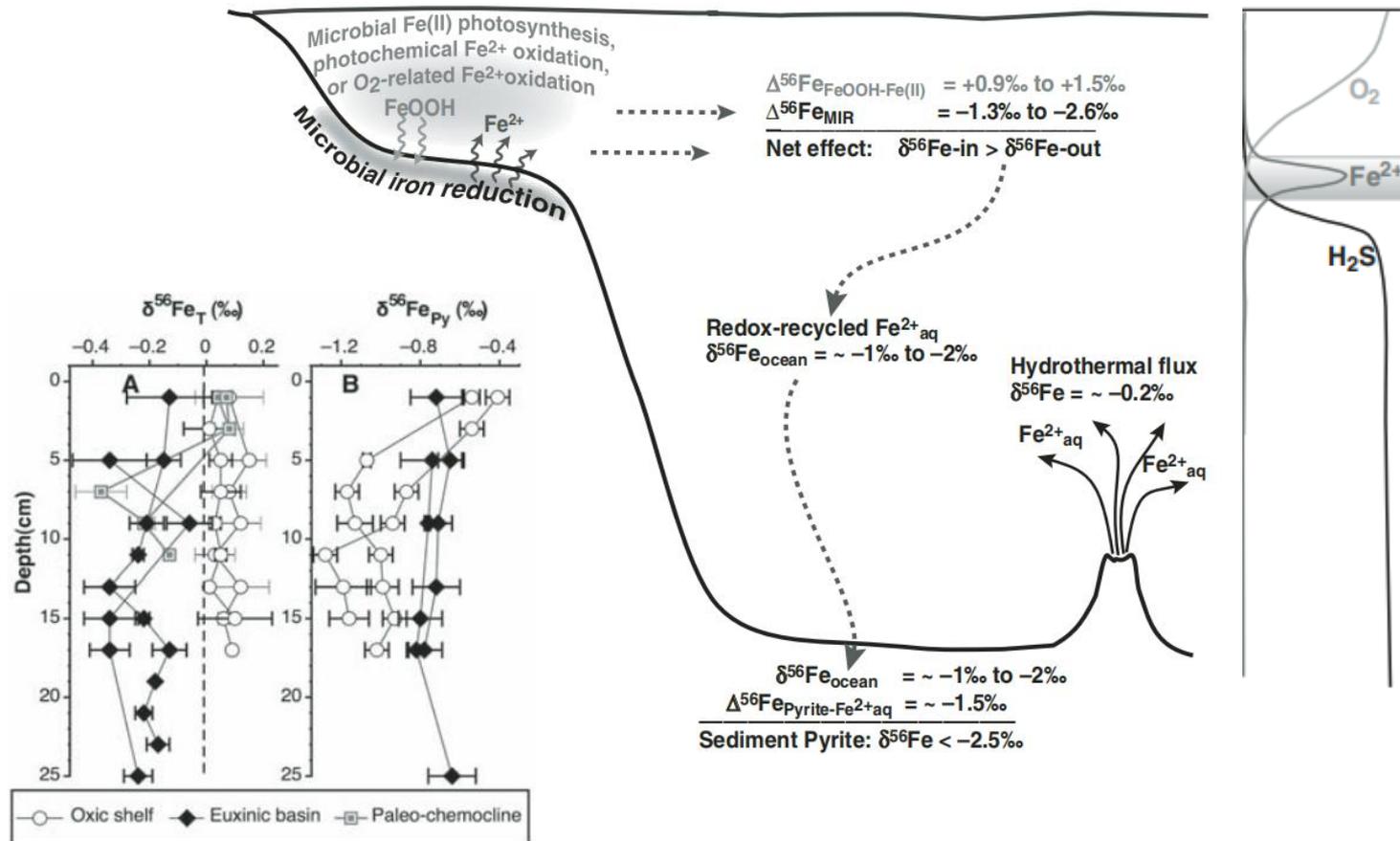


- 大陆架氧化性海泥丢失轻Fe；静置盆地获得轻Fe

Severman et al., 2008

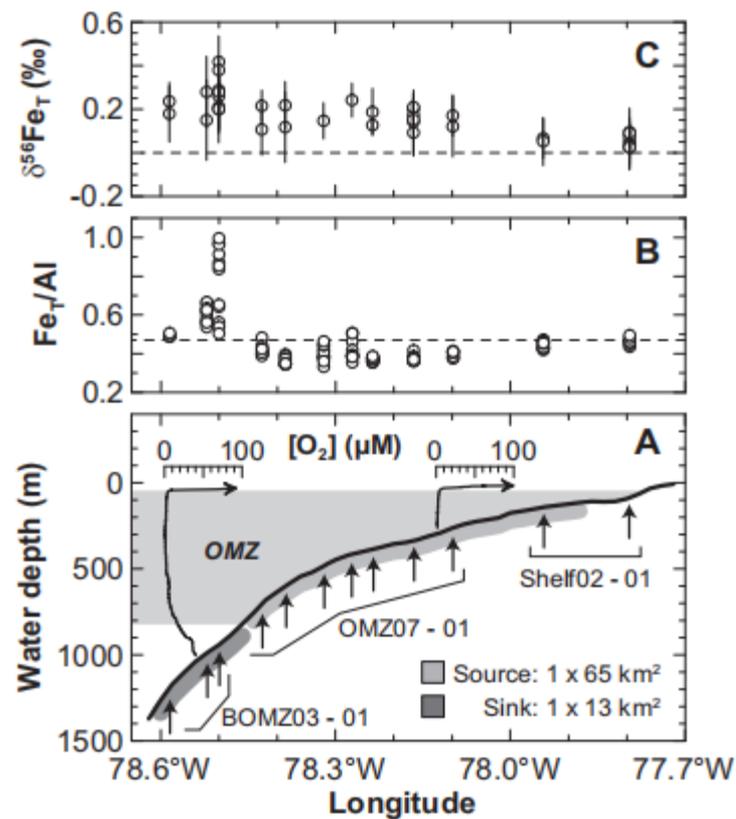
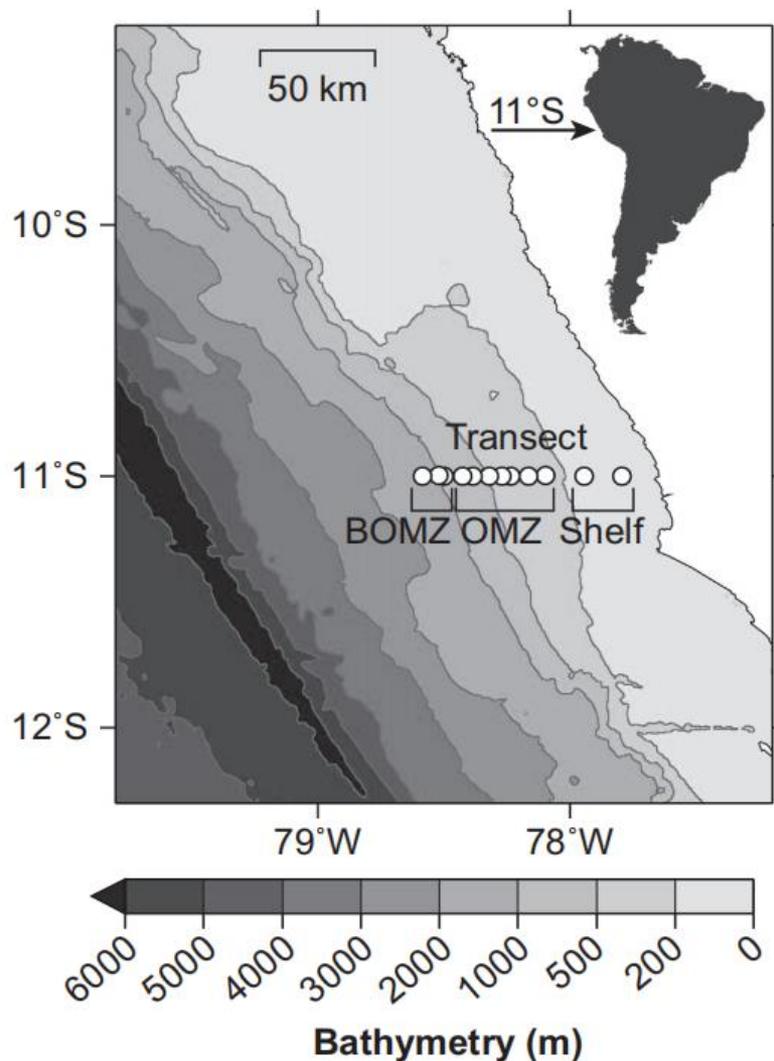
三、浅表氧循环示踪

现代黑海



三、浅表氧循环示踪

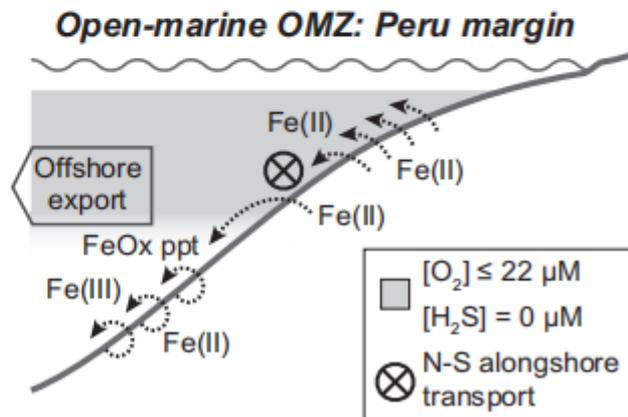
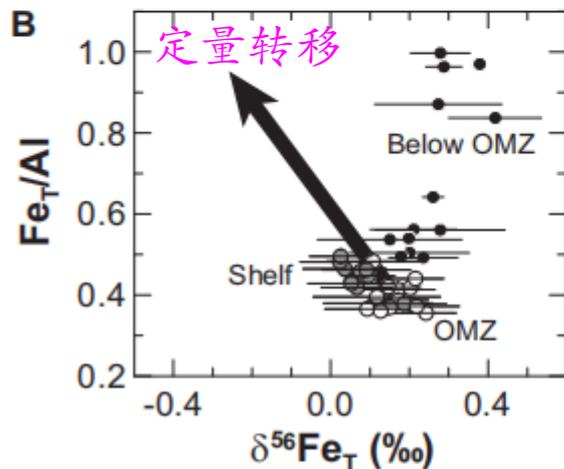
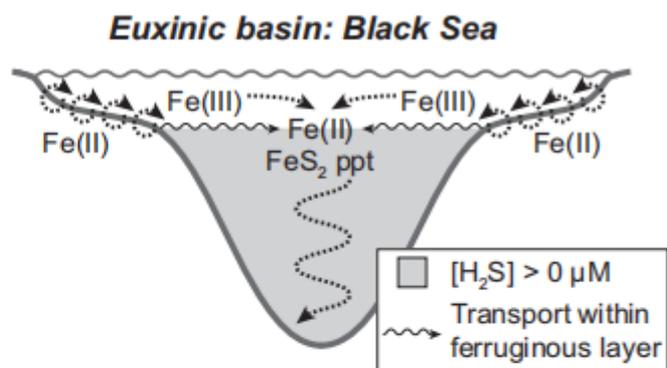
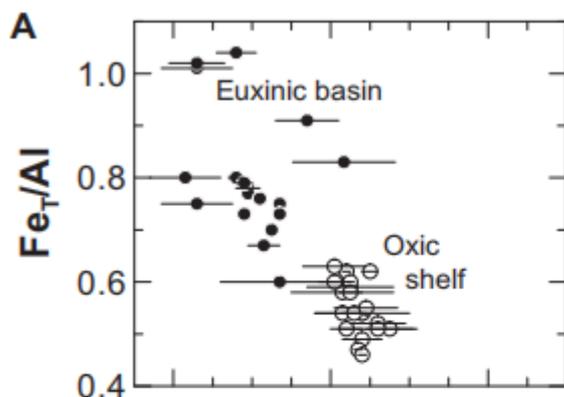
现代秘鲁海岸



Scholz et al., 2014

三、浅表氧循环示踪

现代秘鲁海岸



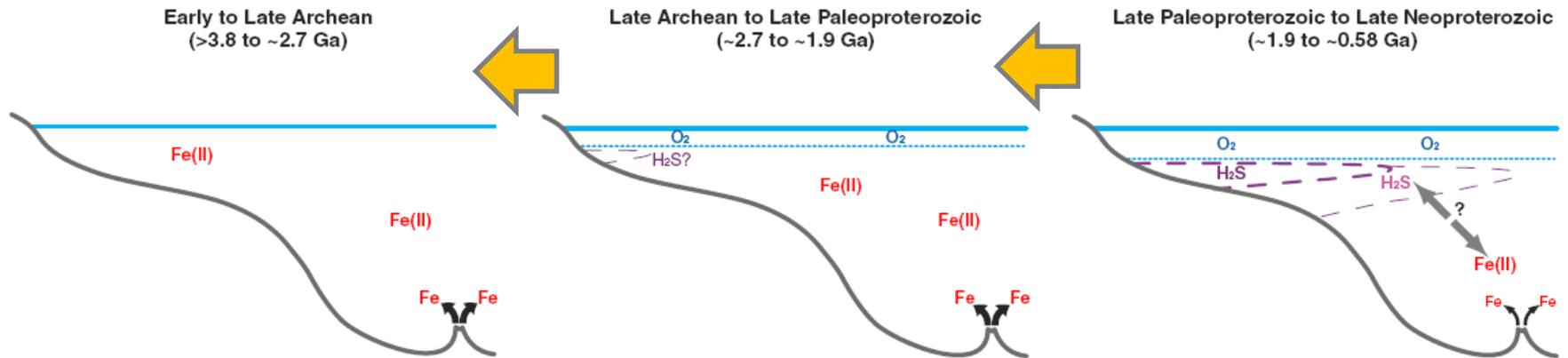
三、浅表氧循环示踪

古代海洋（深时演化）

- 启示:

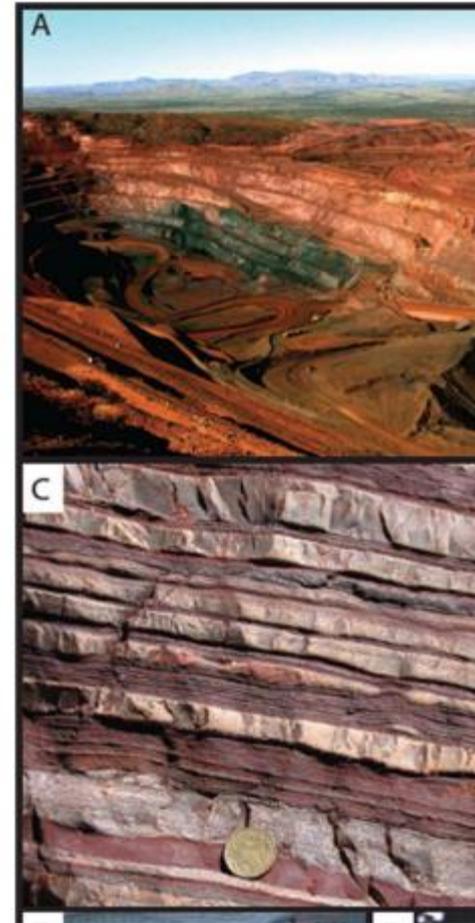
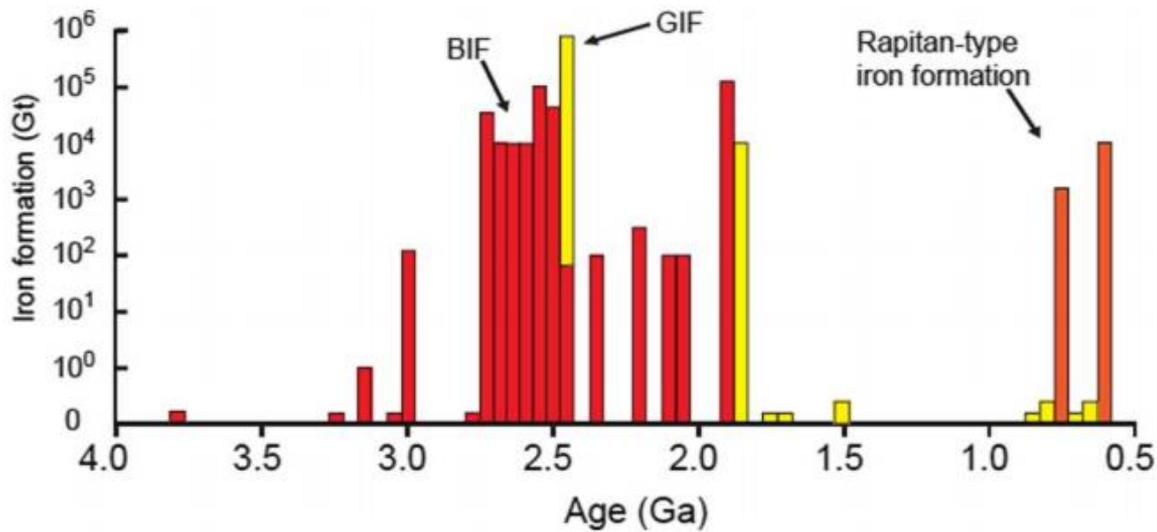
综合不同水深剖面样品的Fe同位素，可示踪海水Fe循环模式

- [OAE、分层海洋]
- 创造性综合研究



三、浅表氧循环示踪

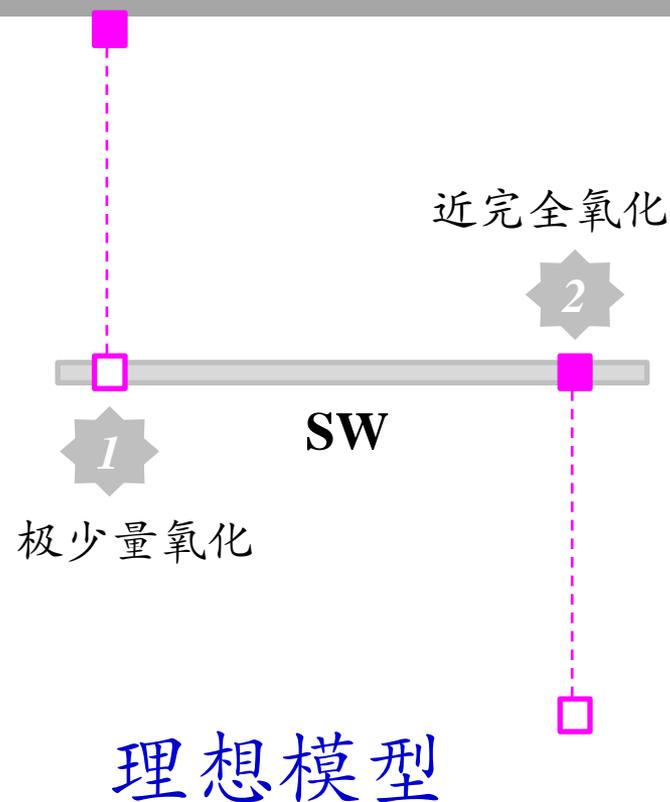
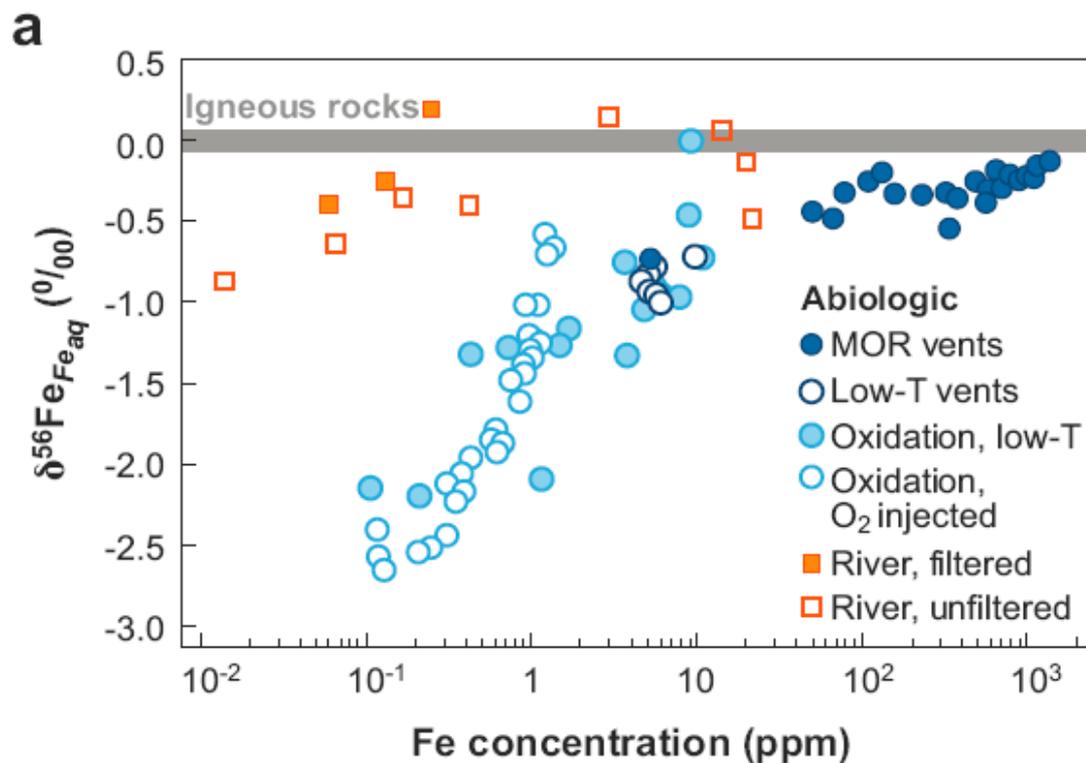
铁建造 (Iron formation)



- 晚太古代、早元古、新元古

三、浅表氧循环示踪

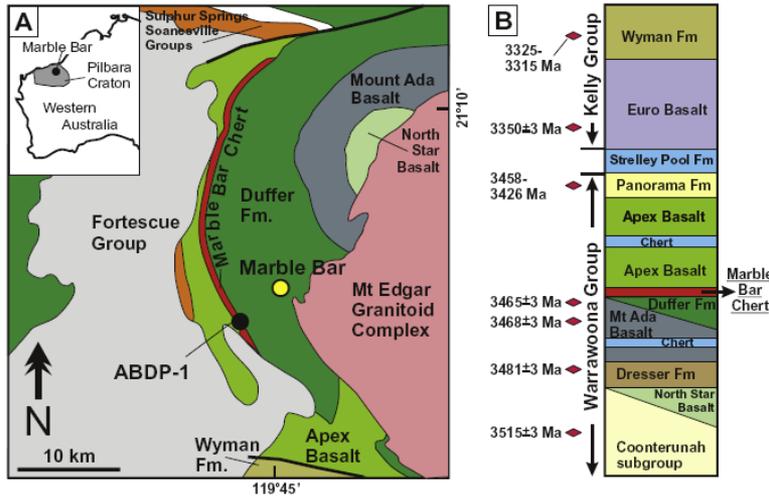
铁建造 (Iron formation)



• $\delta^{56}\text{Fe}_{\text{influx}} \sim -0.2 \sim 0 \text{ ‰}$

$\Delta^{56}\text{Fe}[\text{Goethite-Fe}^{2+}] \sim 3.0 \text{ ‰}$

三、浅表氧循环示踪

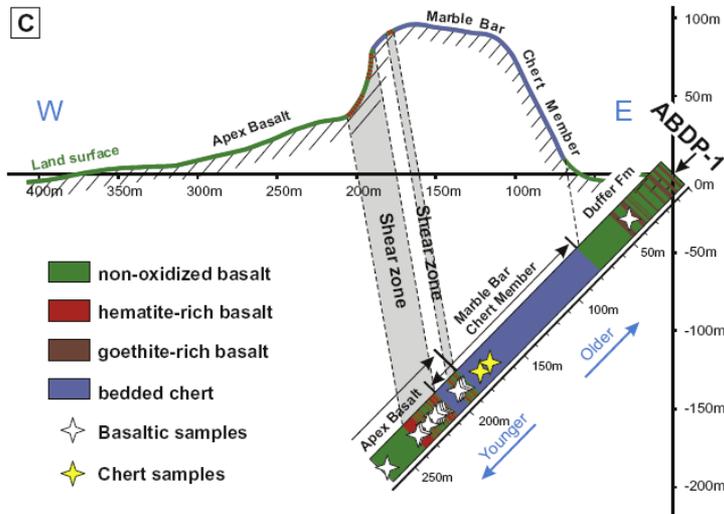


太古代BIF，贫氧海洋

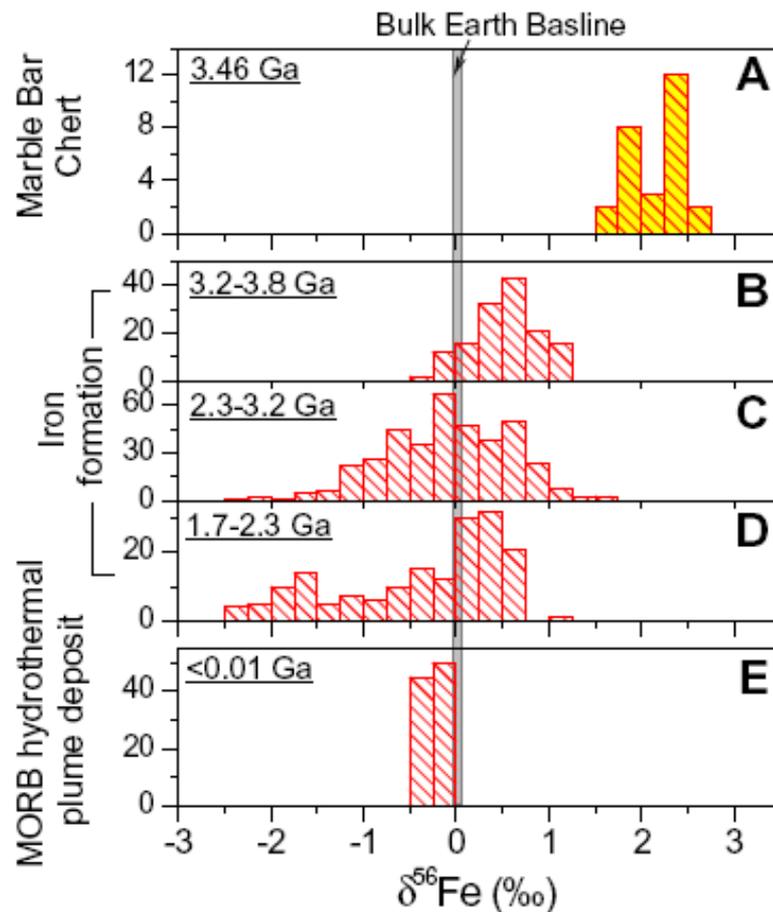
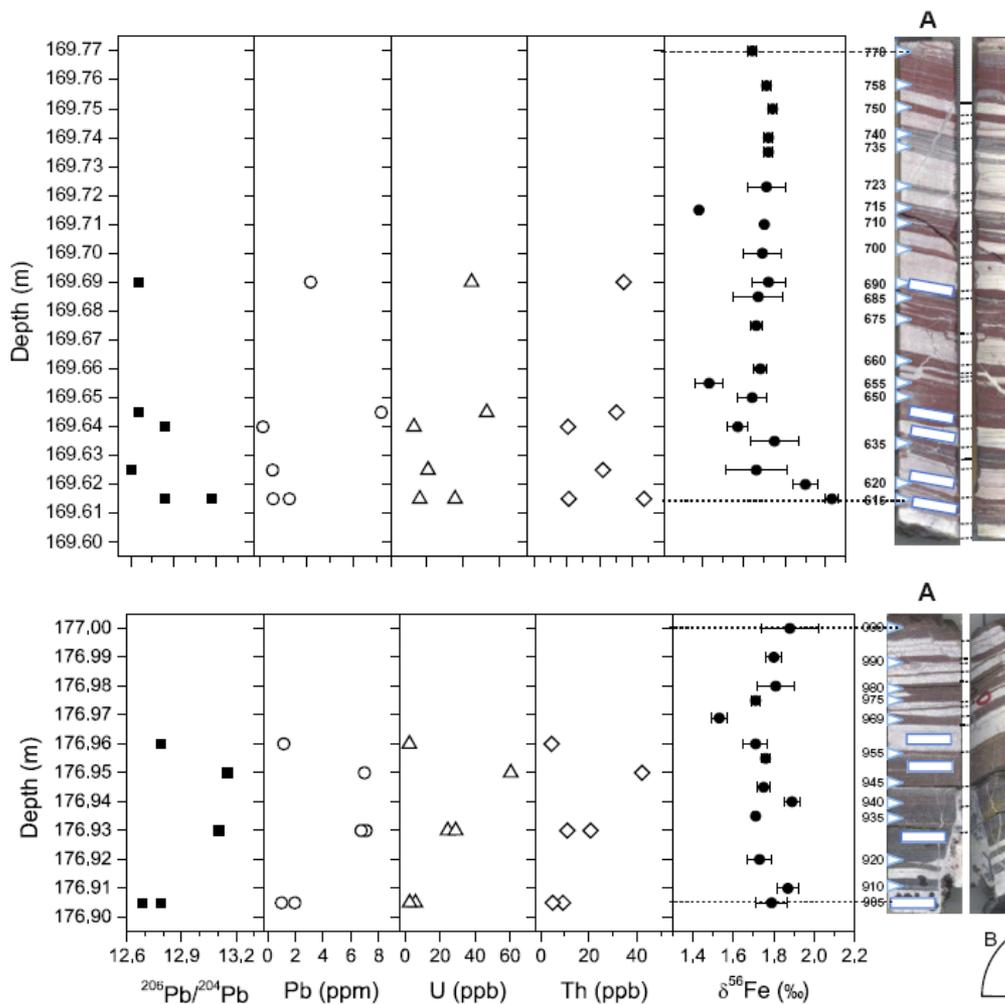
◆ 澳大利亚西北部

Duffer formation

◆ 沉积时代：3.46 Ga

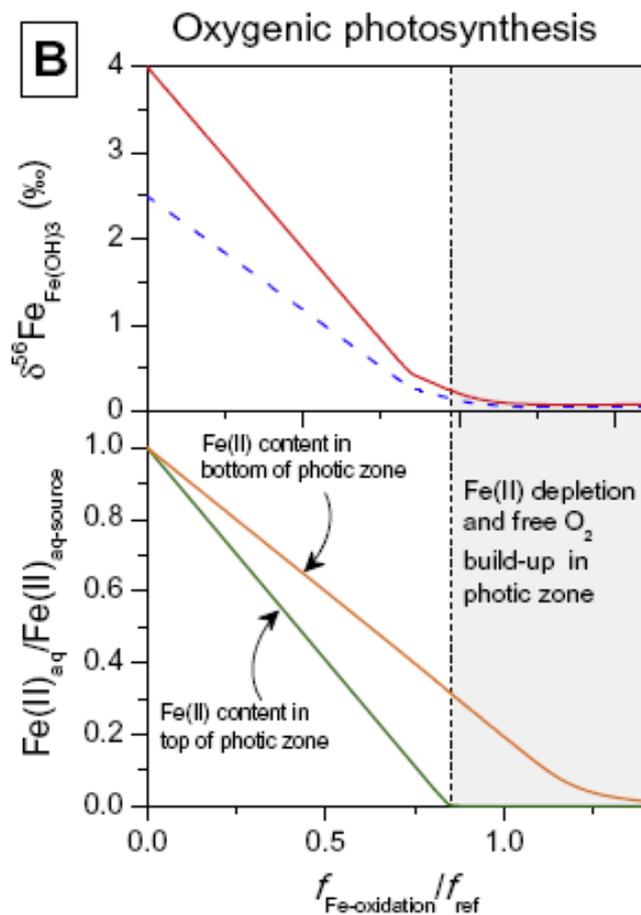
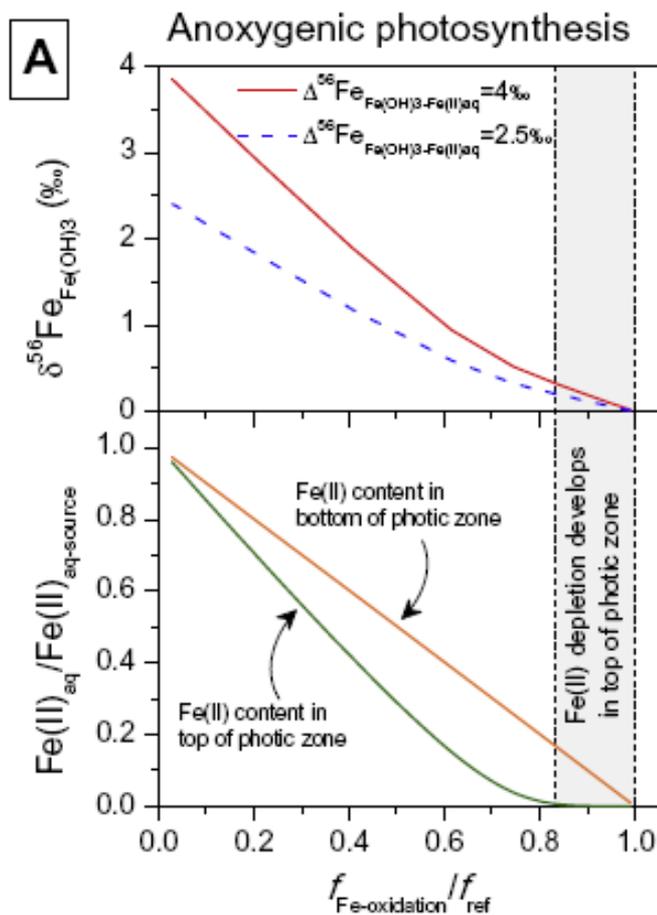


三、浅表氧循环示踪

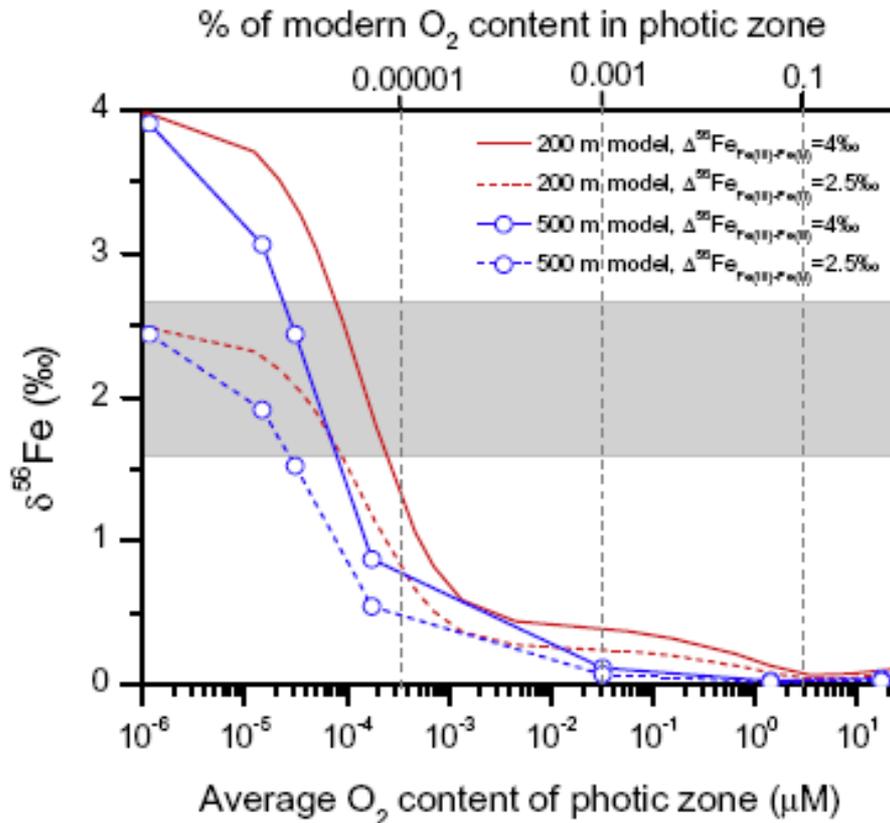


$\delta^{56}\text{Fe}$ 从1.53~2.63‰，显著重于其他时代的BIF

三、浅表氧循环示踪



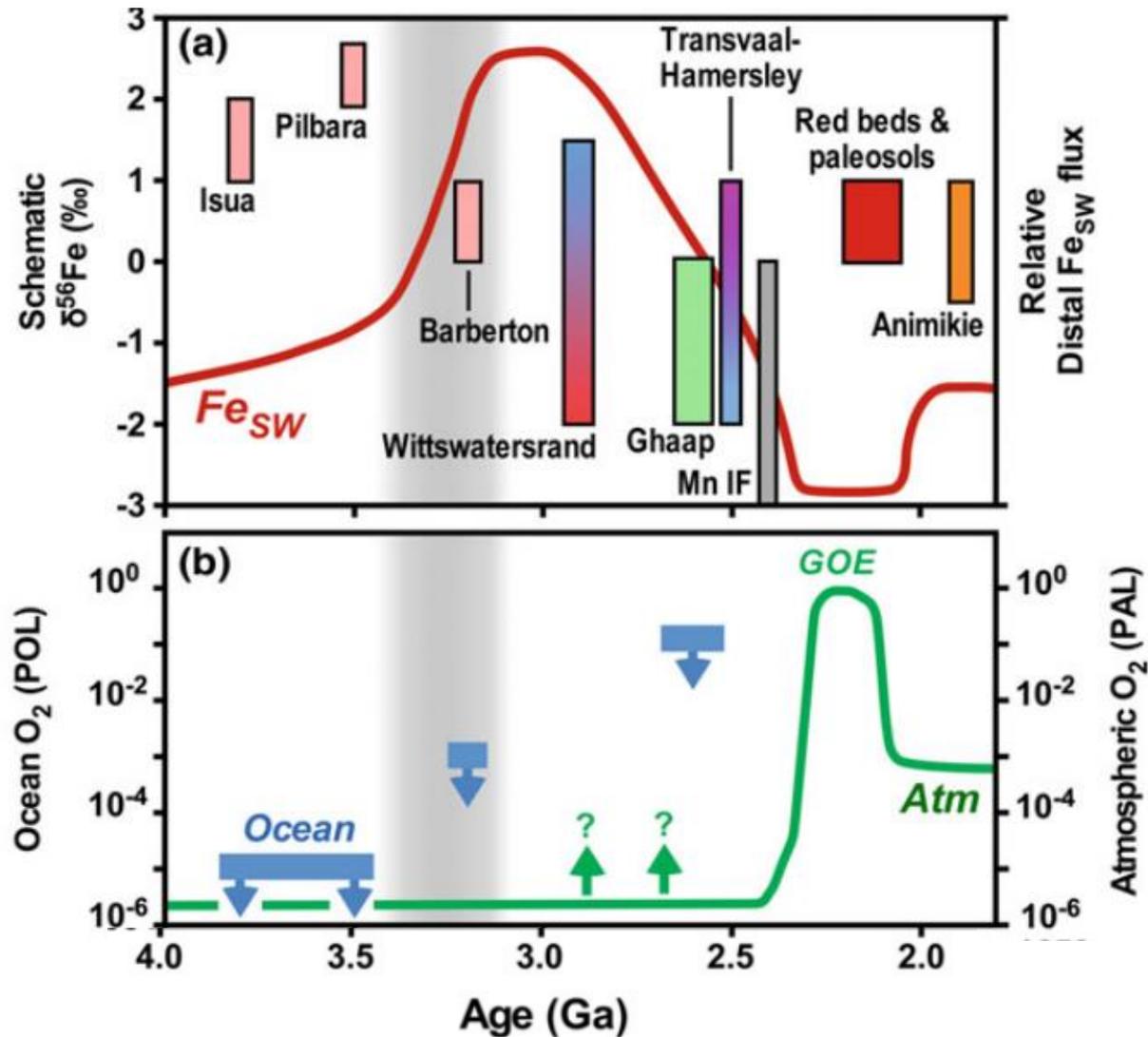
三、浅表氧循环示踪



• 这些BIF形成于低比例氧化，反映当时的海水透光层还存在大量过剩的Fe²⁺，水体含氧量很低。

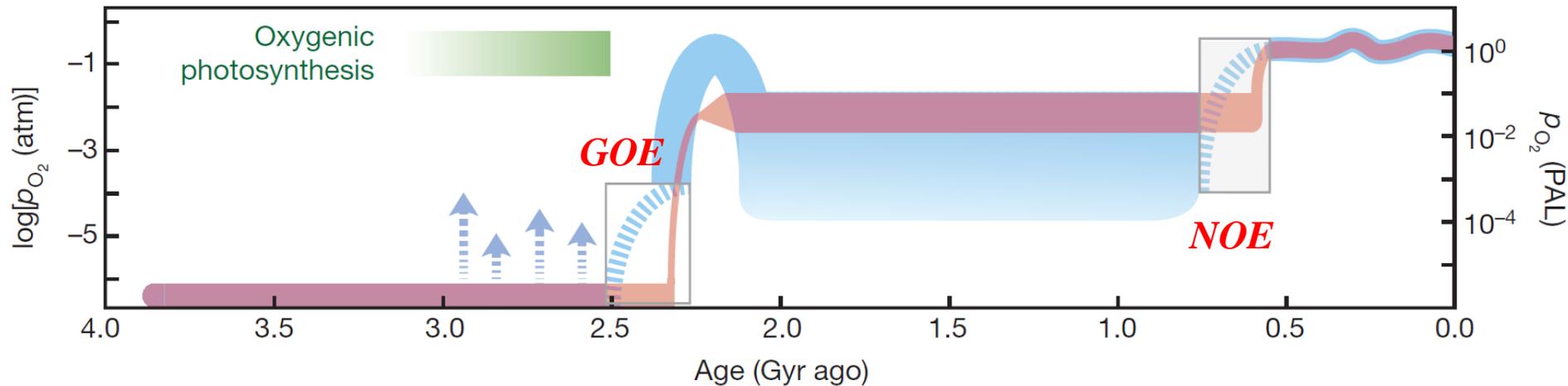
• 经估算，可能仅为现今透光层海水氧含量的0.0003%

四、深部氧循环示踪



四、深部氧循环示踪

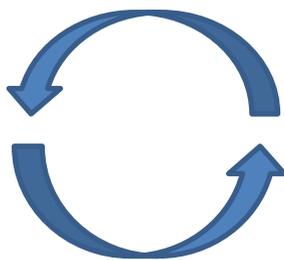
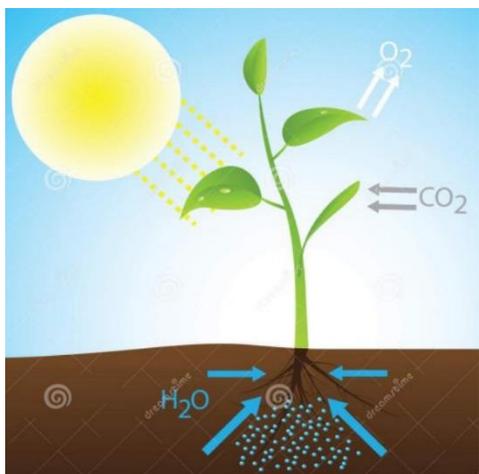
大气氧的演化



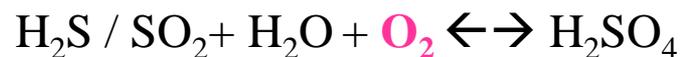
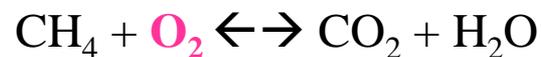
- 地球早期大气几乎无氧，主要经过两次氧化事件达到当今水平。

四、深部氧循环示踪

- 什么机制驱动了大气氧的升高？（长期存在争议）
- 共识和本质问题：



例如：

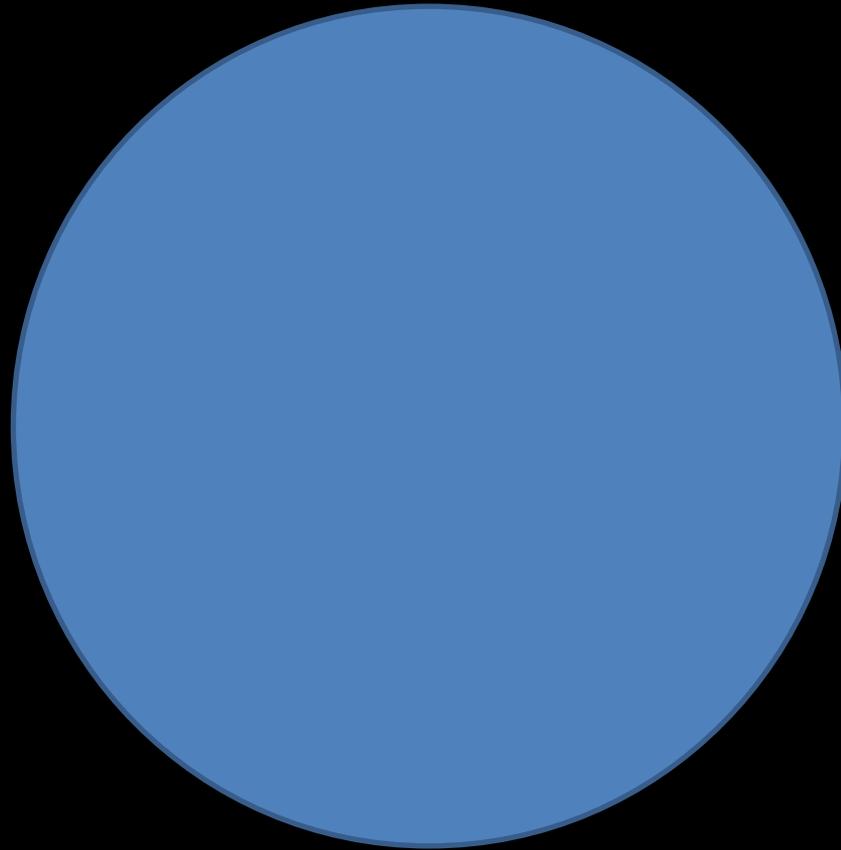


变价元素的循环

氧化剂、还原剂的地质隔离

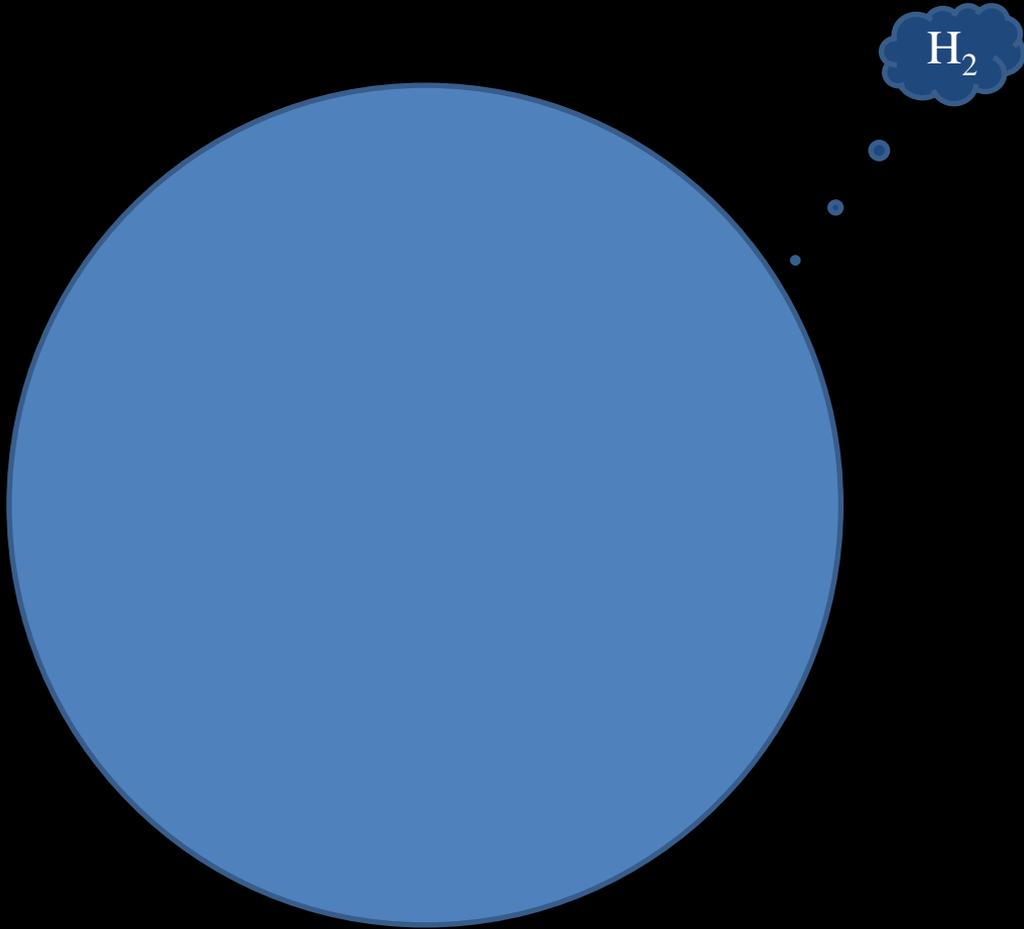
Kasting, CG, 2013; Lyons et al., Nature, 2014

一个封闭系统的氧化还原状态是不变的



引用：刘耘，地球深部氧循环与大气氧升高研讨会[2019]

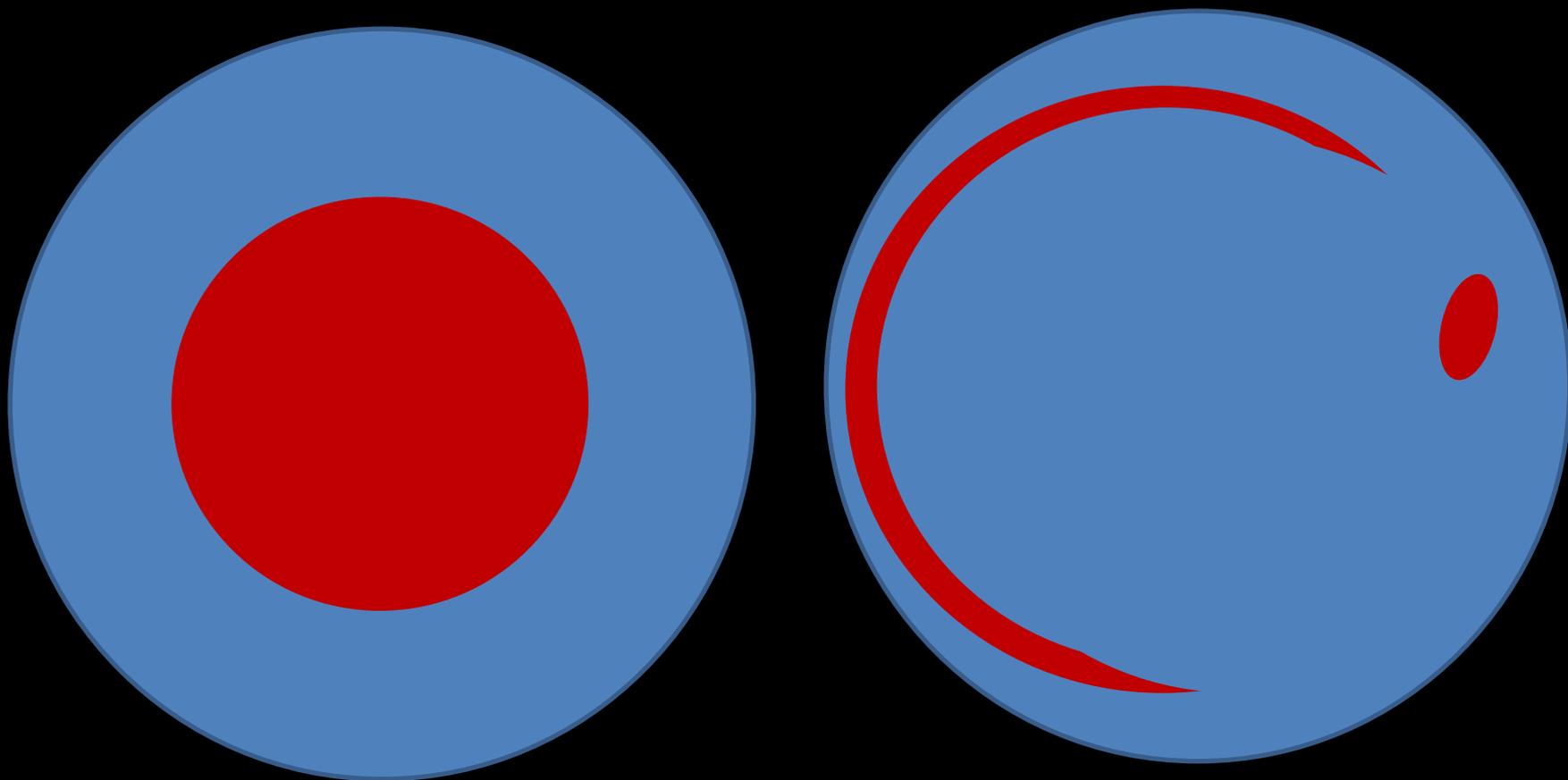
需要有物质移出或者加入



H_2

引用：刘耘，地球深部氧循环与大气氧升高研讨会[2019]

或者出现一些“孤立”的系统，而物质可以**单向**



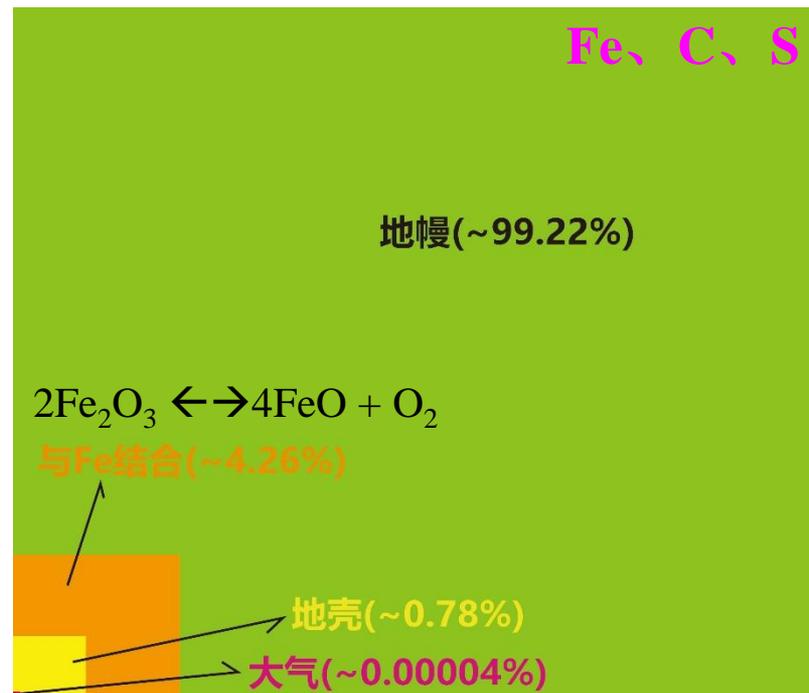
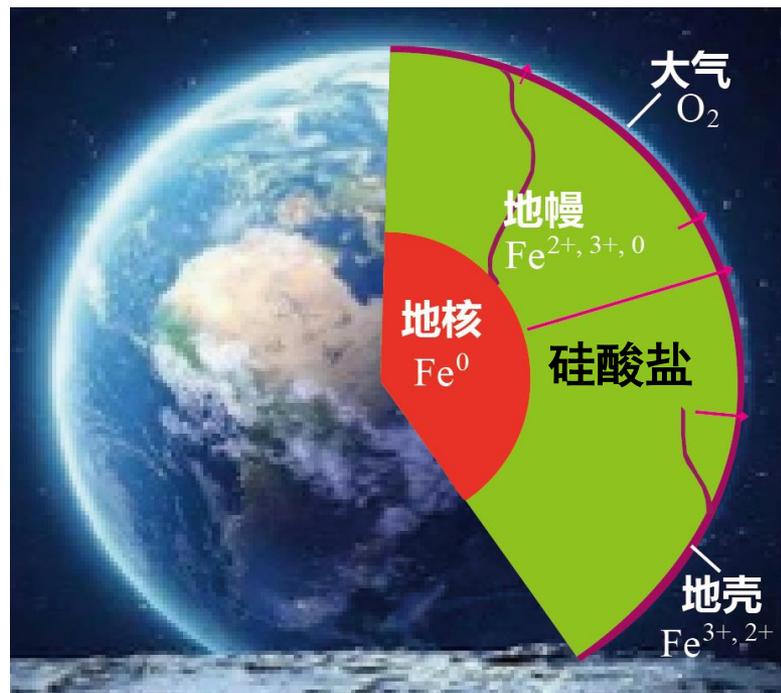
引用：刘耘，地球深部氧循环与大气氧升高研讨会[2019]

四、深部氧循环示踪

什么是深部氧循环？

四、深部氧循环示踪

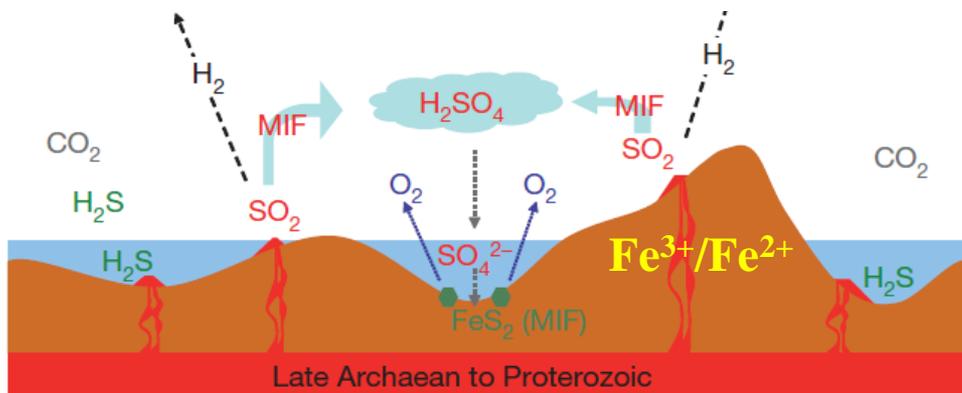
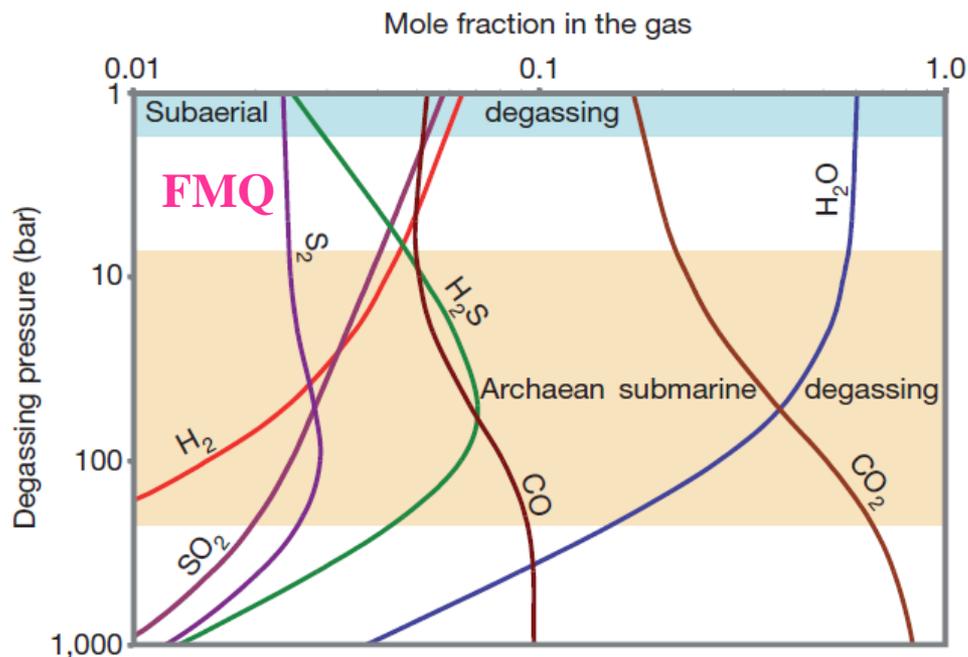
地球的氧



- 氧化还原势在现今地球不同圈层间高度分异
- 地球的氧主要以结合态赋存在深部

四、深部氧循环示踪

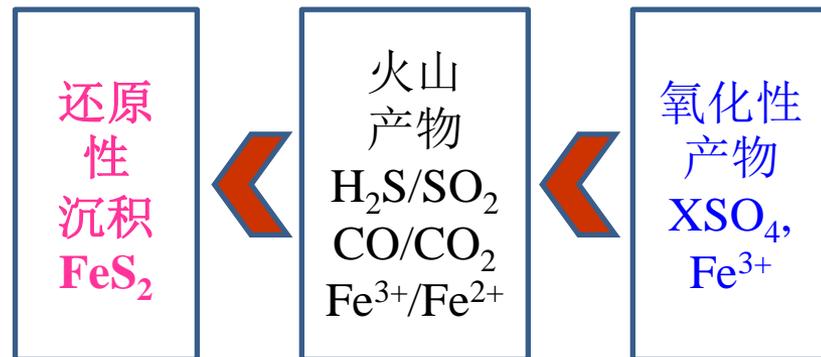
深部氧如何影响大气



e.g., Gaillard et al., Nature, 2011

火山：源 vs. 汇？

氧化性排序

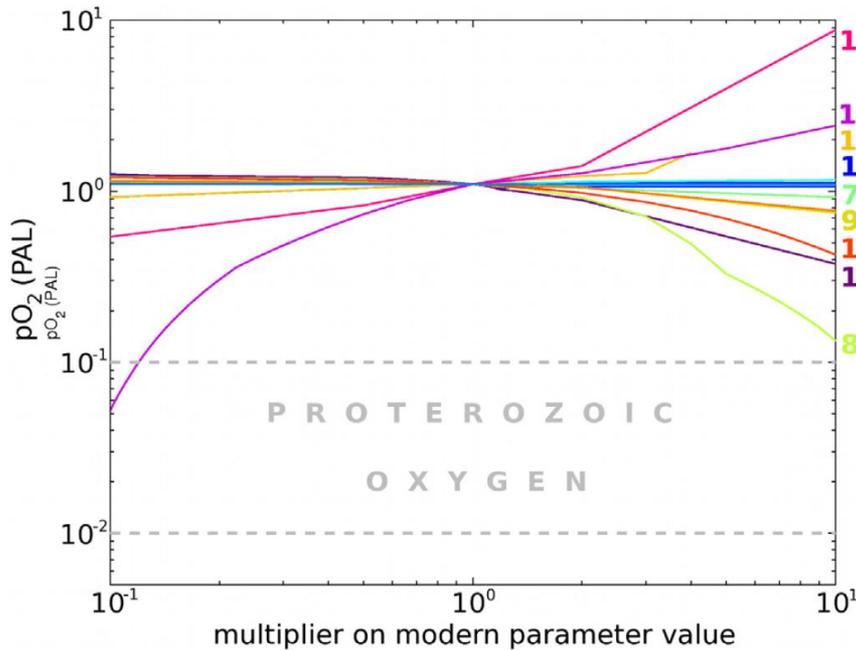


➤ 取决于：

- ✓ 岩浆输出（氧逸度、去气方式）
- ✓ 还原性/氧化性沉积通量比

四、深部氧循环示踪

深部氧如何影响大气

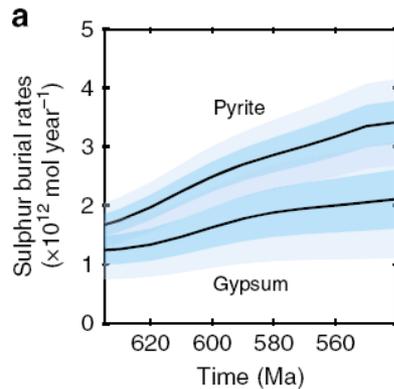
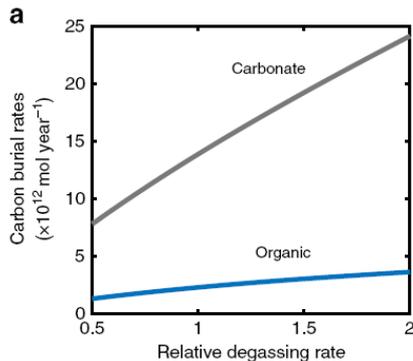


➤ 13, 火山去气

➤ 11, 洋壳氧化

➤ 12, 热液硫化物输入

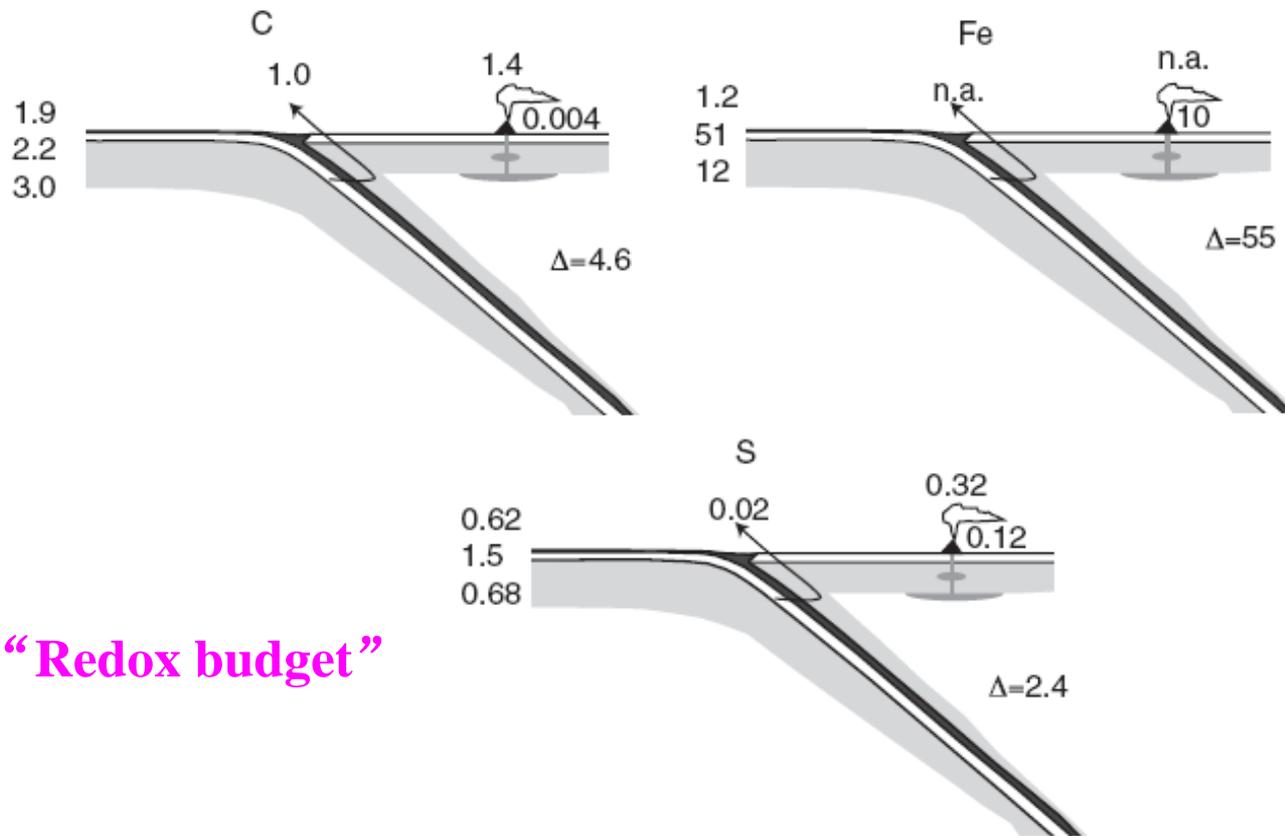
- 现今地球火山去气是O₂的源
- ✓ SO₂、CO₂占主体
- ✓ 部分以有机碳、黄铁矿沉积



*e.g., Gaillard et al., Nature (2011);
Laakso and Schrag, EPSL (2014);
Williams et al., NC (2019)*

四、深部氧循环示踪

俯冲带是重要的汇

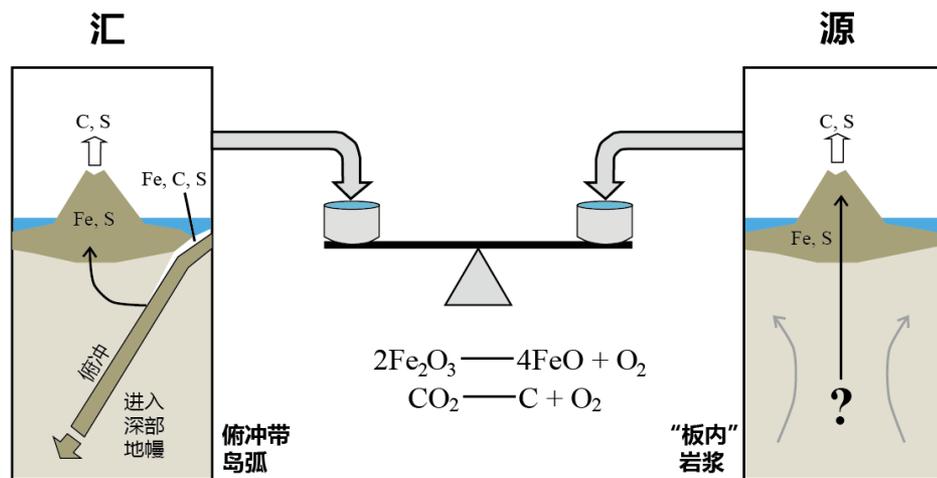


“Redox budget”

- 现代俯冲带是 O_2 的汇；该通量可在3.5 Ma内完全消耗大气 O_2

四、深部氧循环示踪

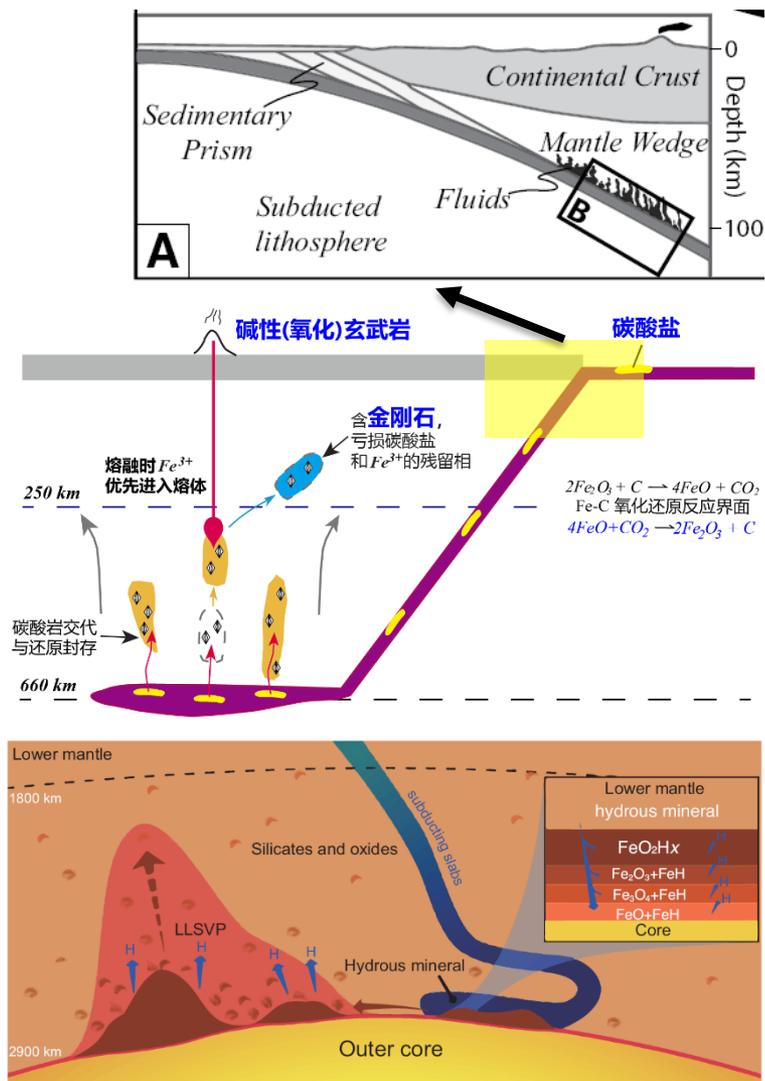
深部氧循环



- 地球浅表和深部间通过俯冲和火山作用实现氧化还原势交换
(变价元素交换)
- 深部氧循环在大气氧演化中发挥重要作用

一、深部氧循环与大气氧演化

深部氧循环的研究内容



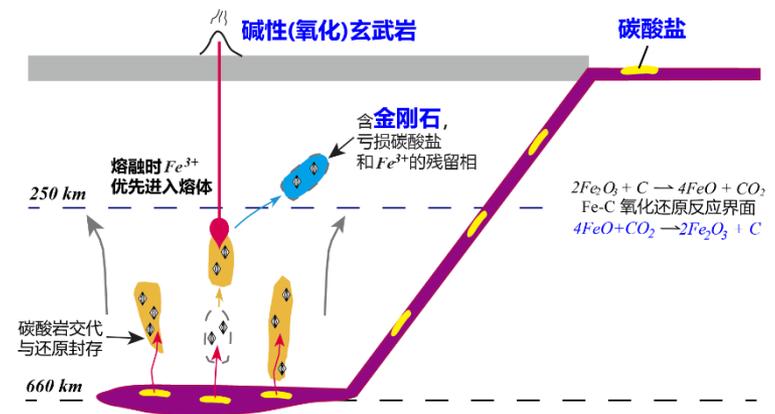
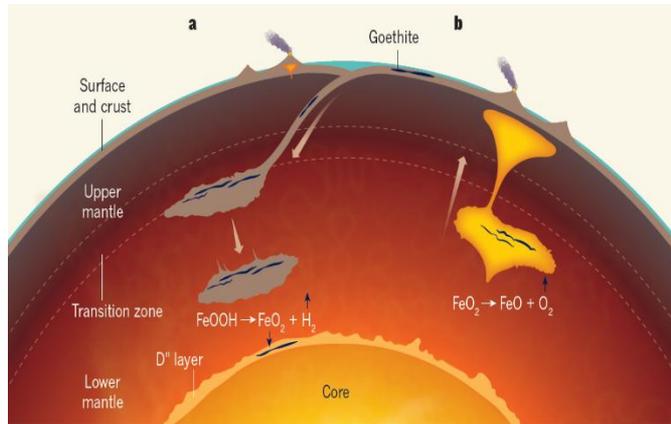
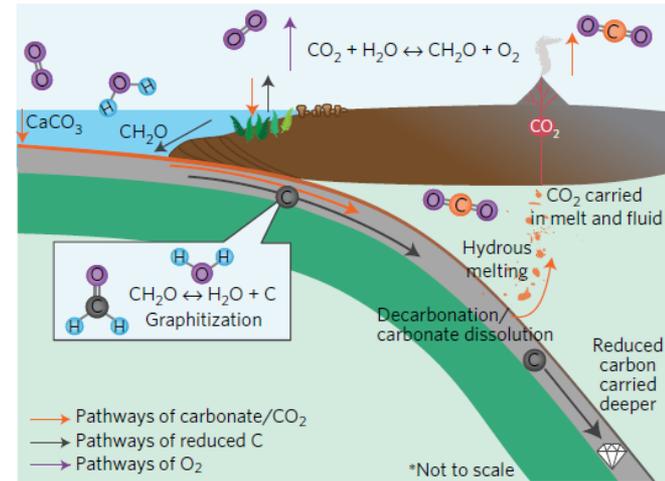
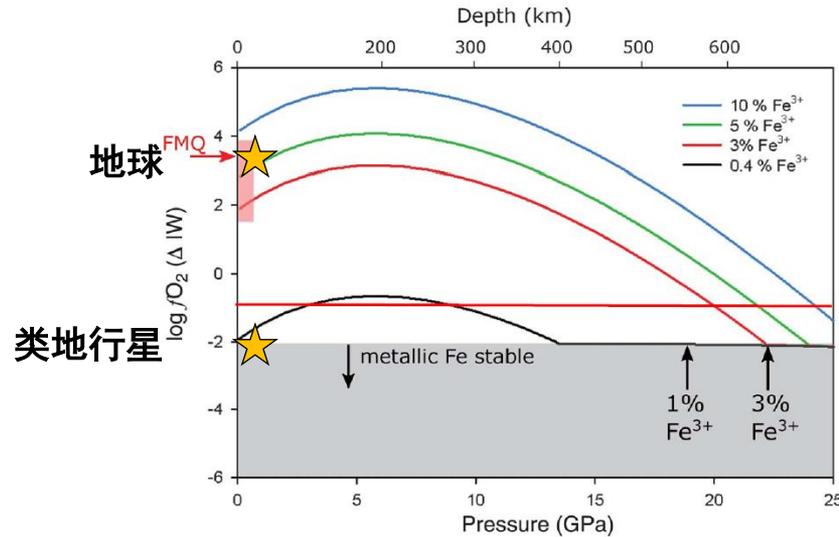
- 深部氧循环通过变价元素还原/氧化态的交换和地质封闭的方式，改变深部地球与浅表圈层间的氧化还原势

- 研究内容：
变价元素在俯冲带及深部地幔甚至核幔边界的赋存状态、循环方式和循环通量

Debret et al, Geology (2016); Hu et al., Nature (2016); Duncan and Dasgupta, NG (2017); Mao et al., NSR (2017); He et al., EPSL (2019); Chen et al., GCA (2019)

四、深部氧循环示踪

深部氧循环改变地表氧逸度的几种方式

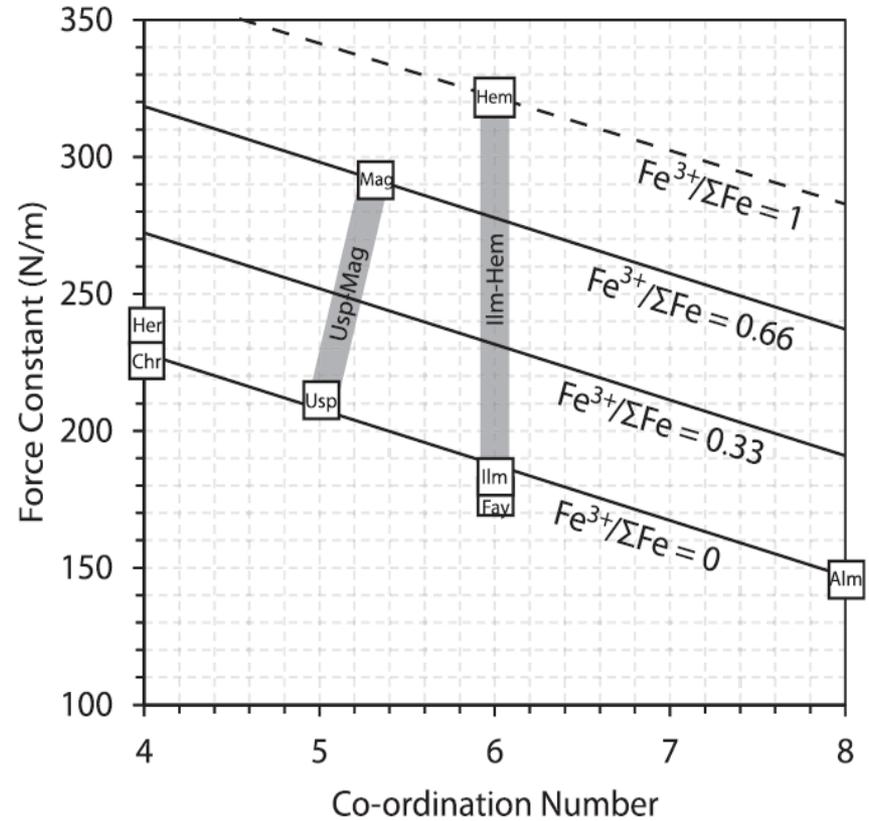
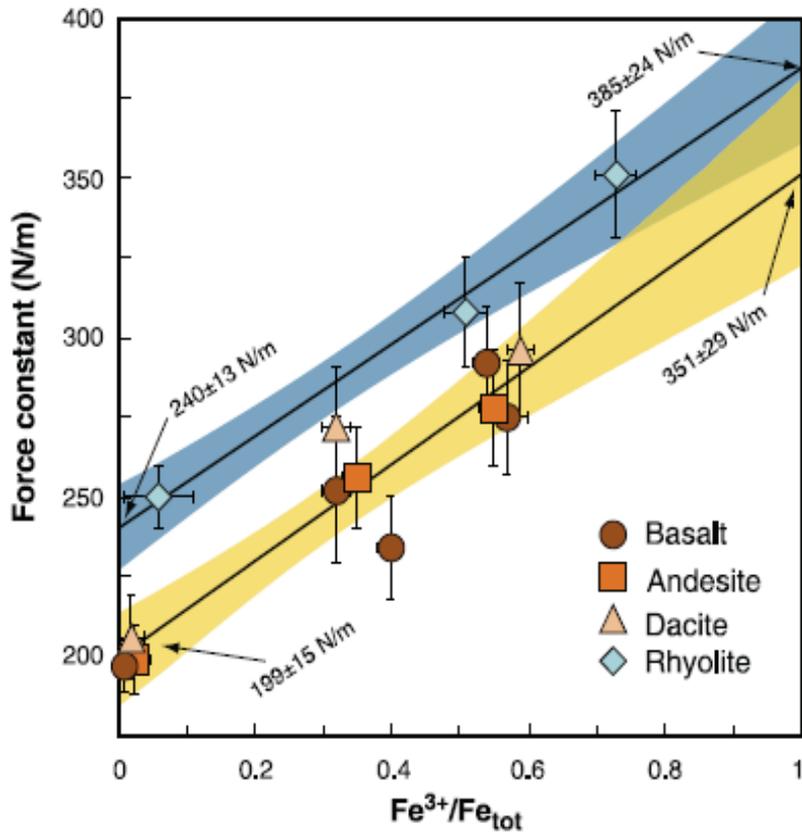


Hu et al., Nature (2016); Duncan and Dasgupta, NG (2017); Mao et al., NSR (2017); He et al., EPSL (2019); Armstrong et al., Science (2019)

四、深部氧循环示踪

铁同位素示踪深部氧循环原理

四、深部氧循环示踪

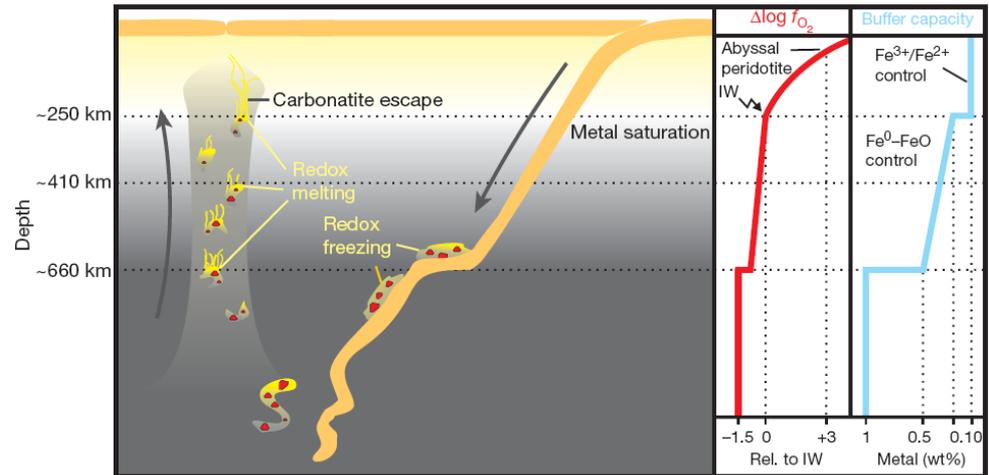


- 分馏主要受控于物相间Fe³⁺、Fe²⁺、Fe⁰的分配

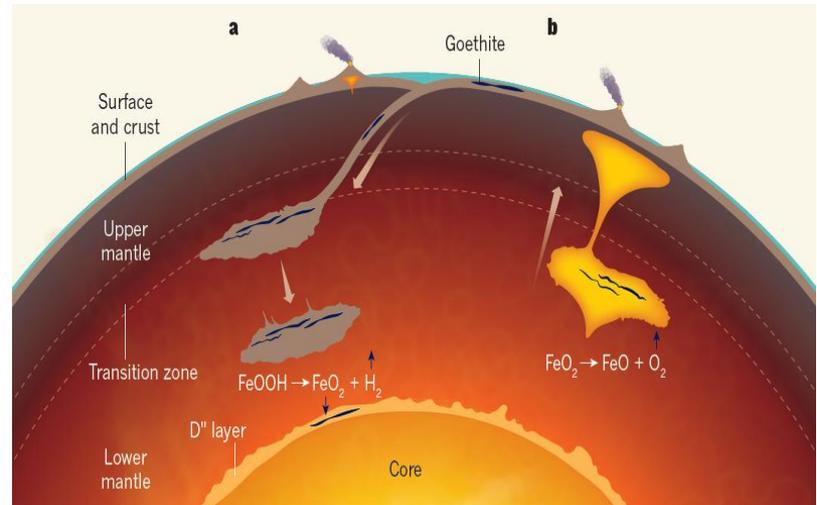
Polyakov and Mineev, GCA (2000); Dauphas et al, EPSL (2014); Sossi and O'Neil, GCA (2017)

四、深部氧循环示踪

铁(Fe^0 , Fe^{2+} , Fe^{3+})循环驱动深部氧循环



- Fe是深部地球最重要的氧化还原缓冲
- 多种反应机制本质上由Fe的相变诱导



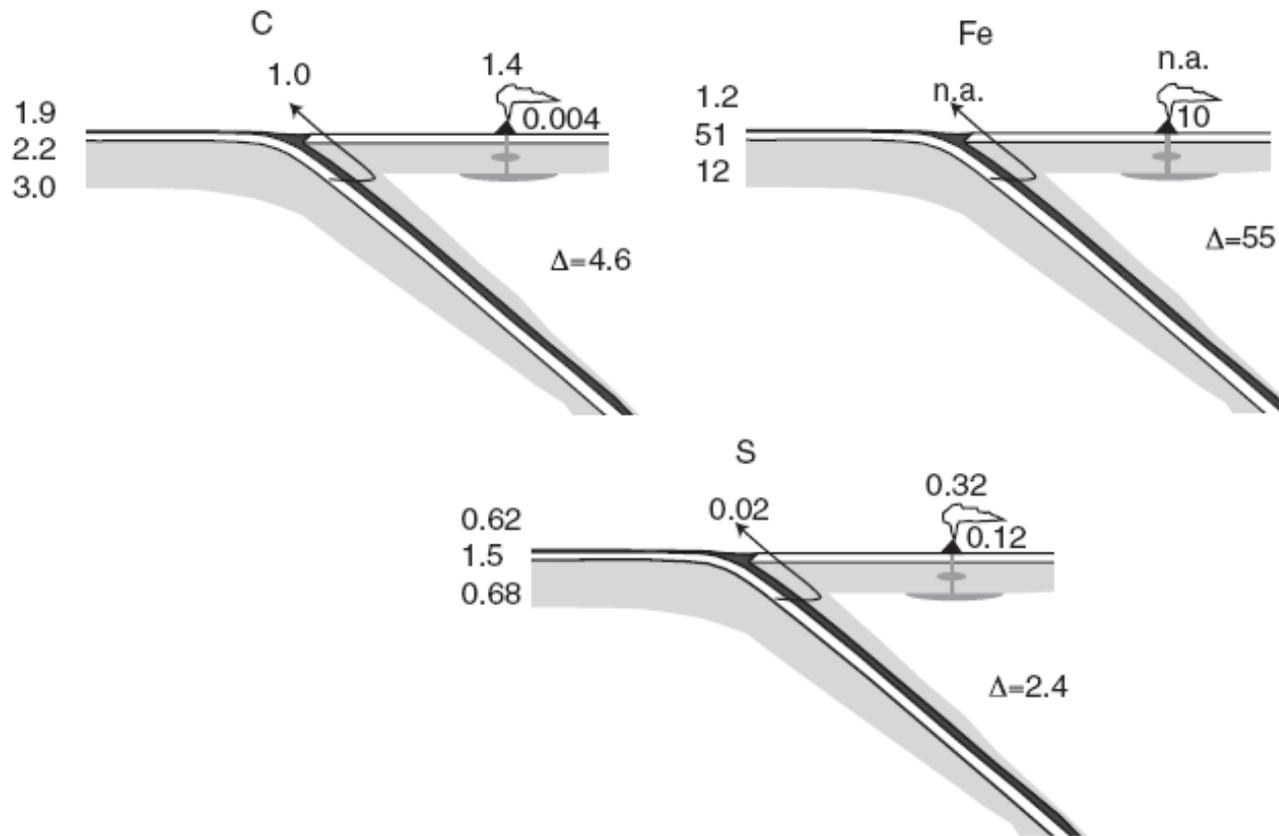
Frost et al, Nature (2004); Rohrbach and Schmidt, Nature (2011); Hu et al., Nature (2016)

四、深部氧循环示踪

铁同位素示踪俯冲带氧循环

四、深部氧循环示踪

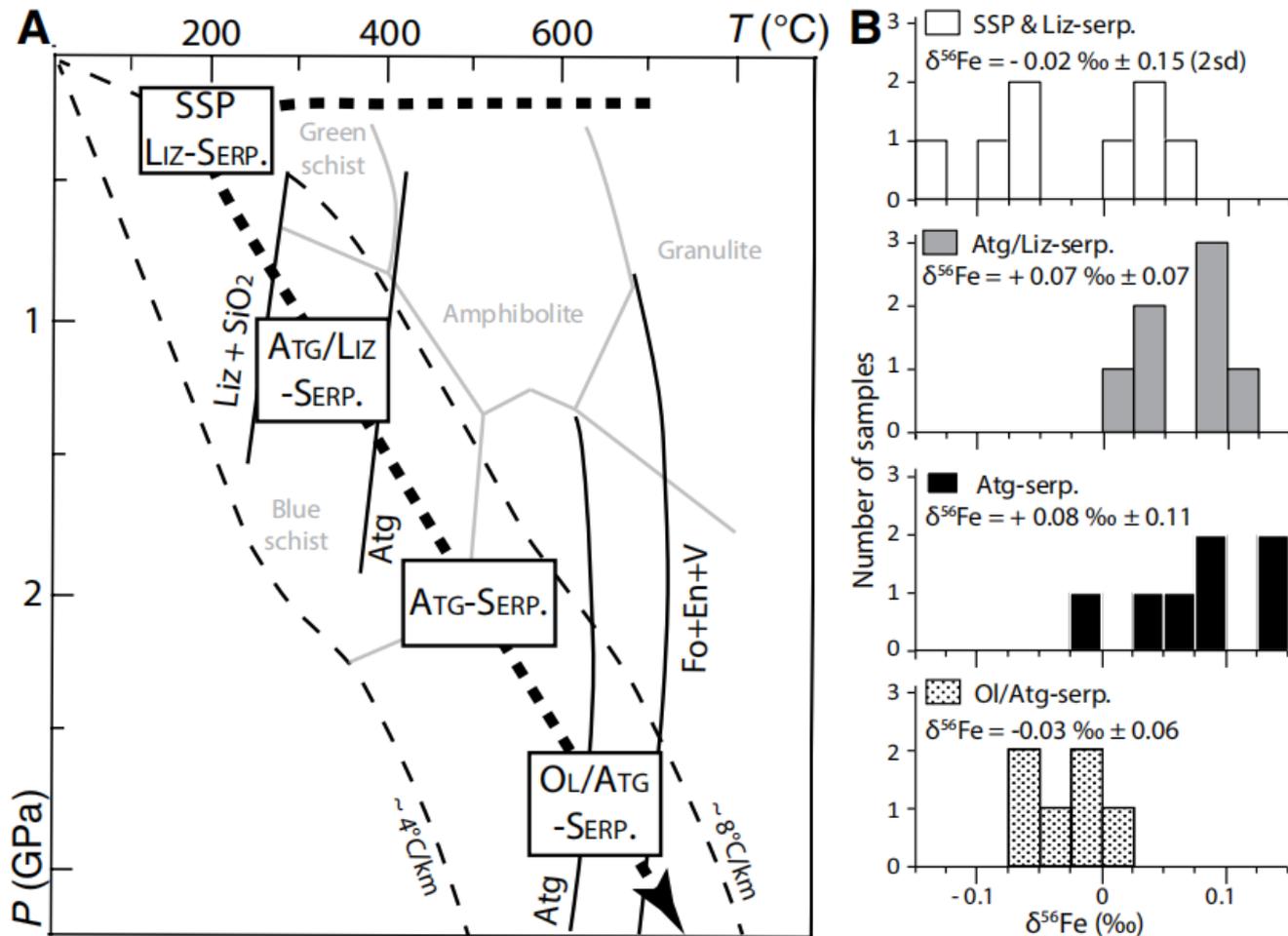
俯冲带是重要的汇



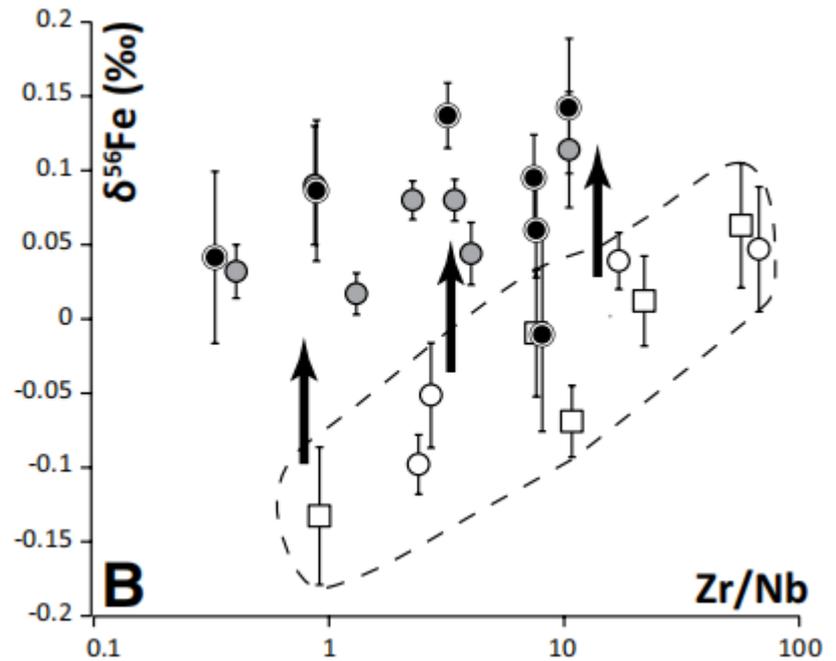
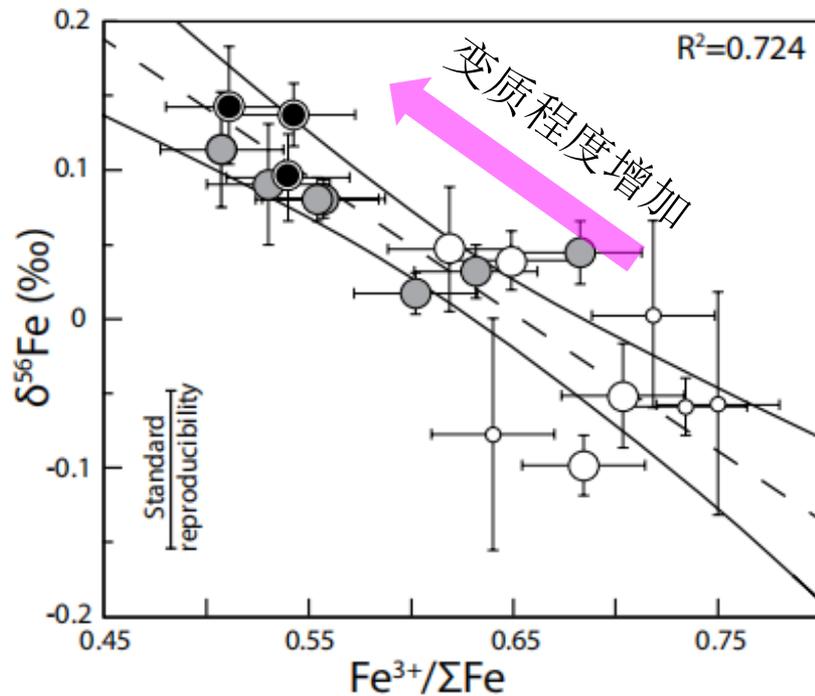
俯冲输入 vs. 岛弧岩浆输出?

四、深部氧循环示踪

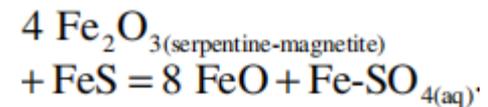
阿尔卑斯实例 (蛇纹岩脱水)



四、深部氧循环示踪



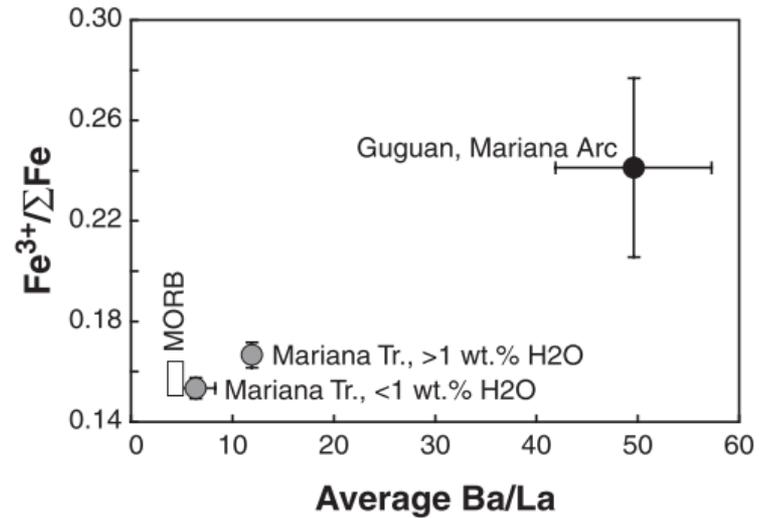
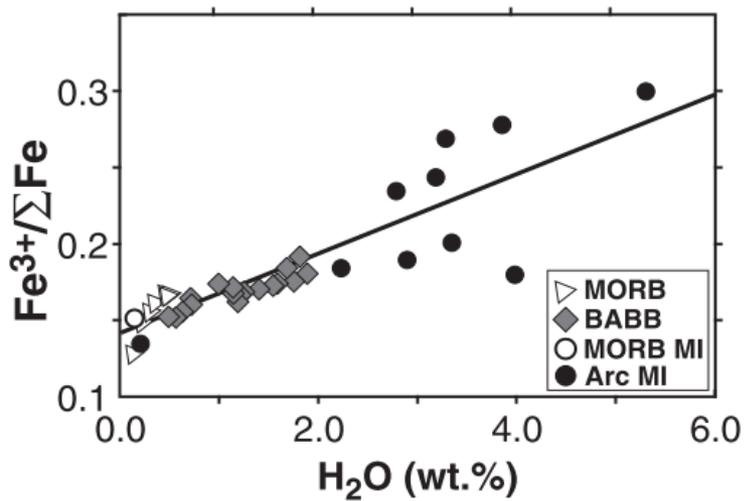
- 丢失轻Fe同位素 (亚铁)
- $Fe^{3+}/\Sigma Fe$ 降低指示氧化还原反应



产生氧化性流体!

四、深部氧循环示踪

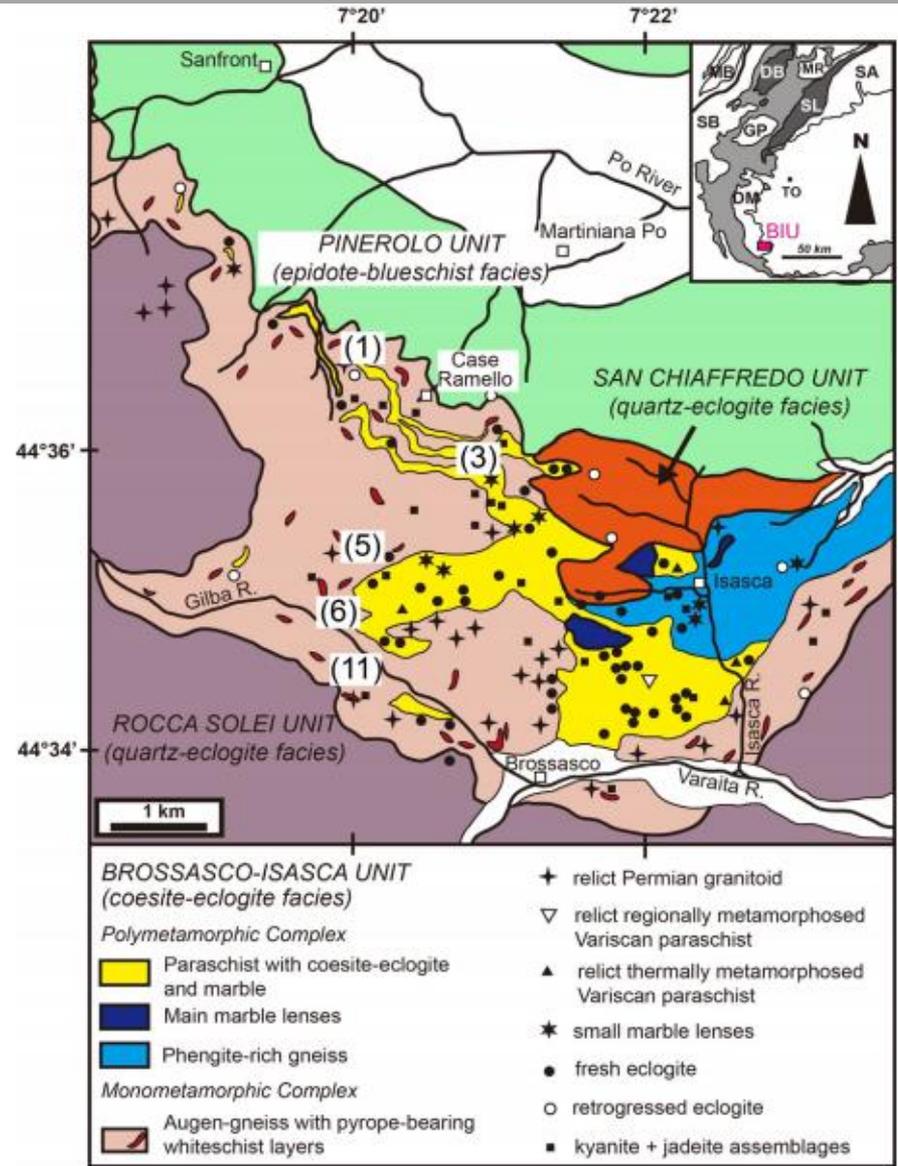
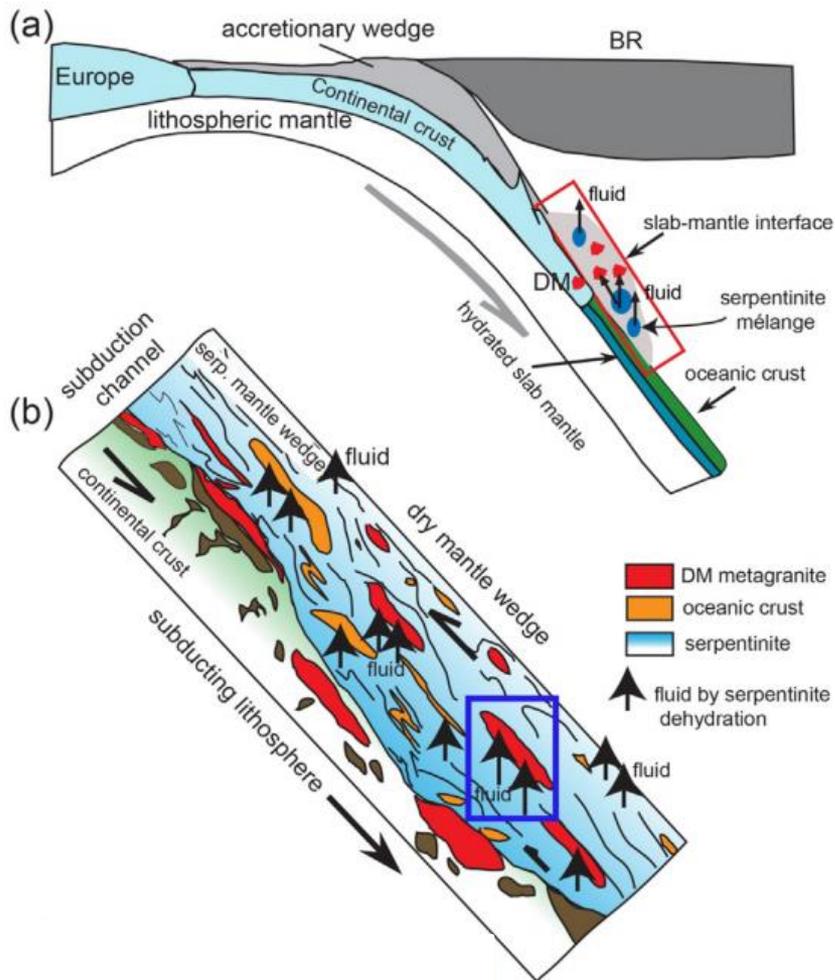
岛弧岩浆



部分氧化剂通过岛弧岩浆返回

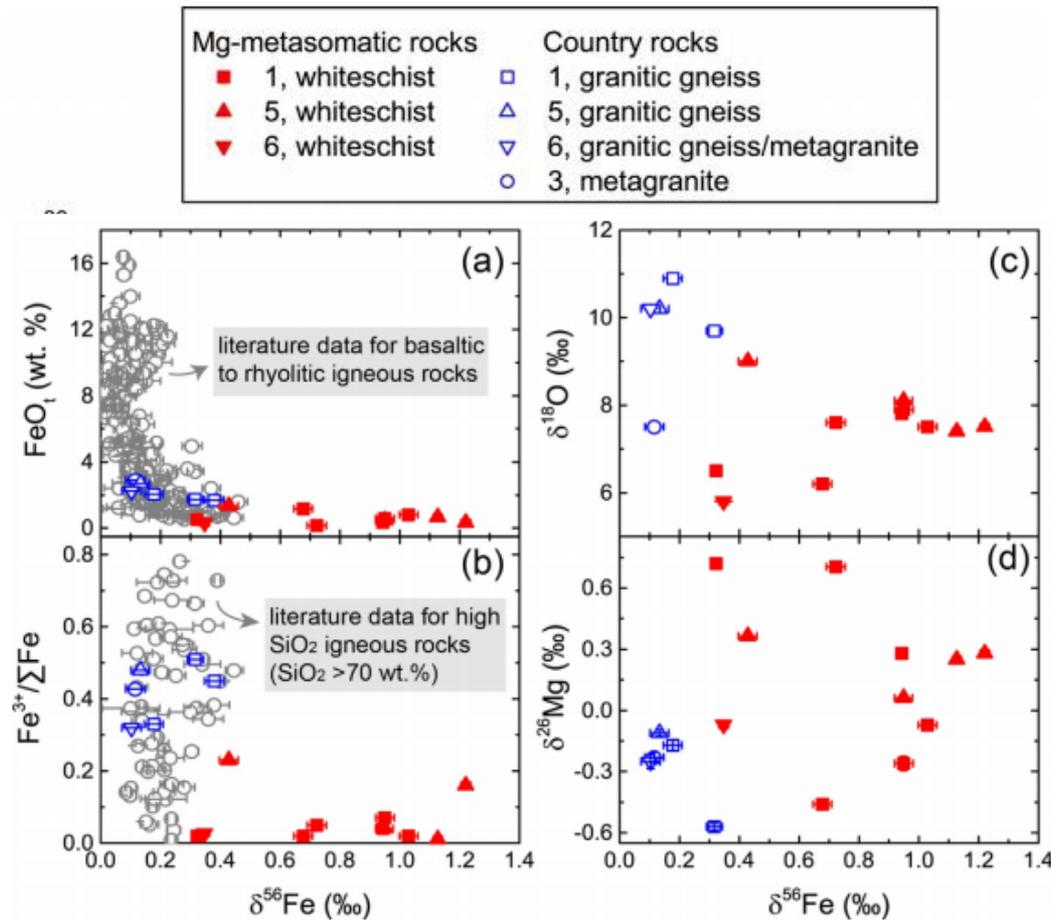
四、深部氧循环示踪

阿尔卑斯白片岩



四、深部氧循环示踪

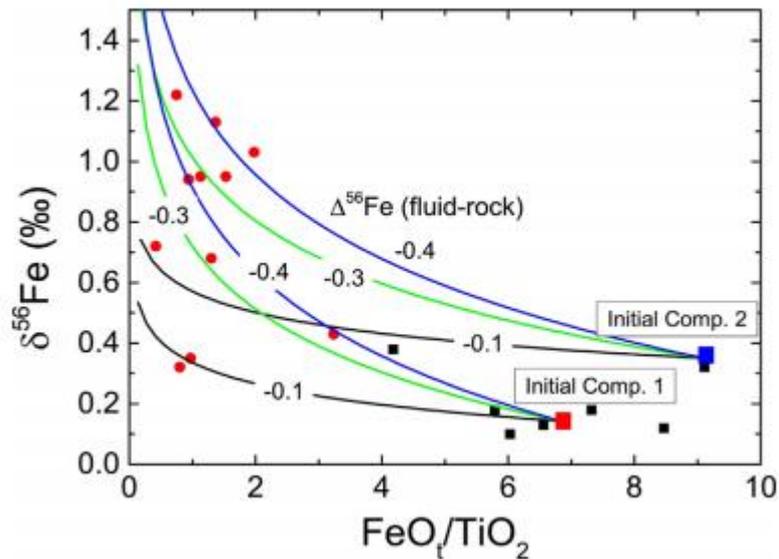
阿尔卑斯白片岩



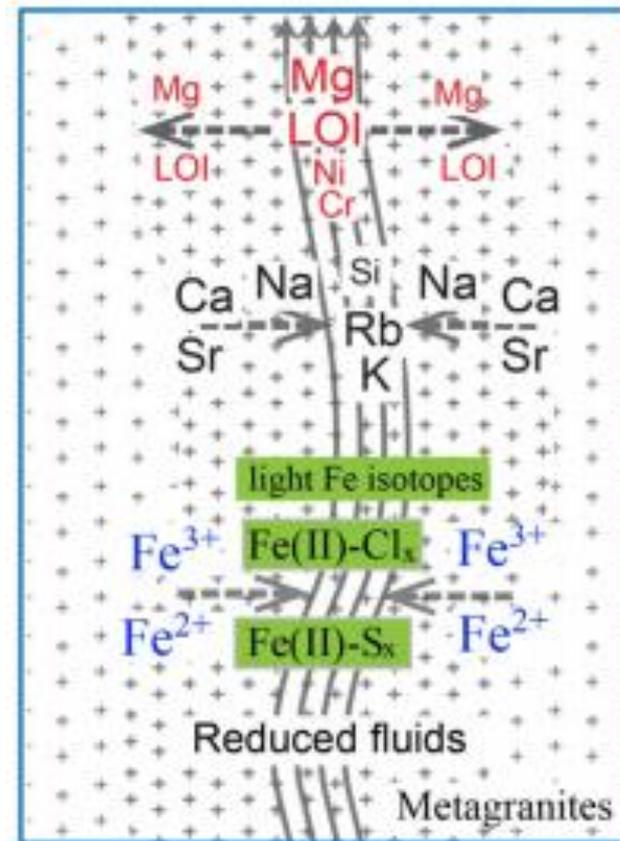
- O-Mg同位素指示外源流体
- 丢失轻Fe同位素 (亚铁)
- $\text{Fe}^{3+}/\sum\text{Fe}$ 降低指示氧化还原反应

四、深部氧循环示踪

阿尔卑斯白片岩



还原性流体!

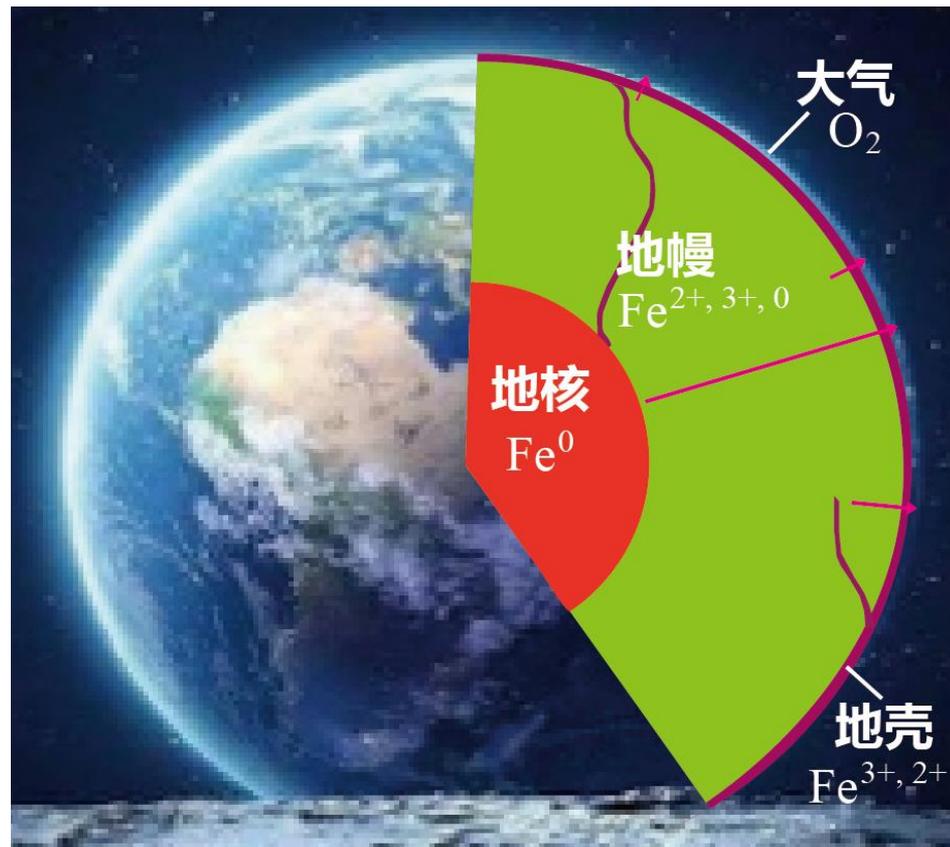


四、深部氧循环示踪

铁同位素示踪 “深部” 氧循环

四、深部氧循环示踪

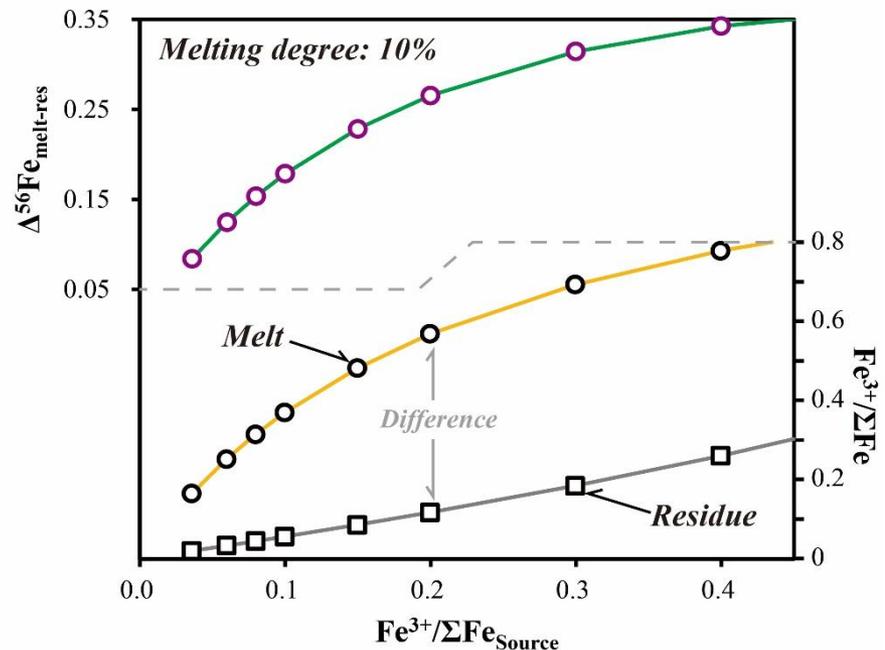
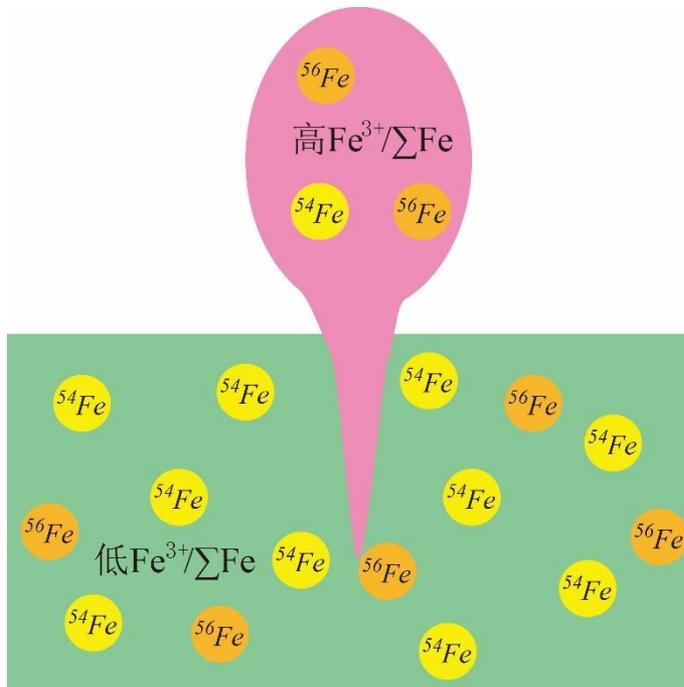
- 研究深部氧循环, 主要研究对象是慢源岩浆岩
- 关键: 岩浆的氧逸度及其成因



四、深部氧循环示踪

铁同位素示踪深部氧循环原理

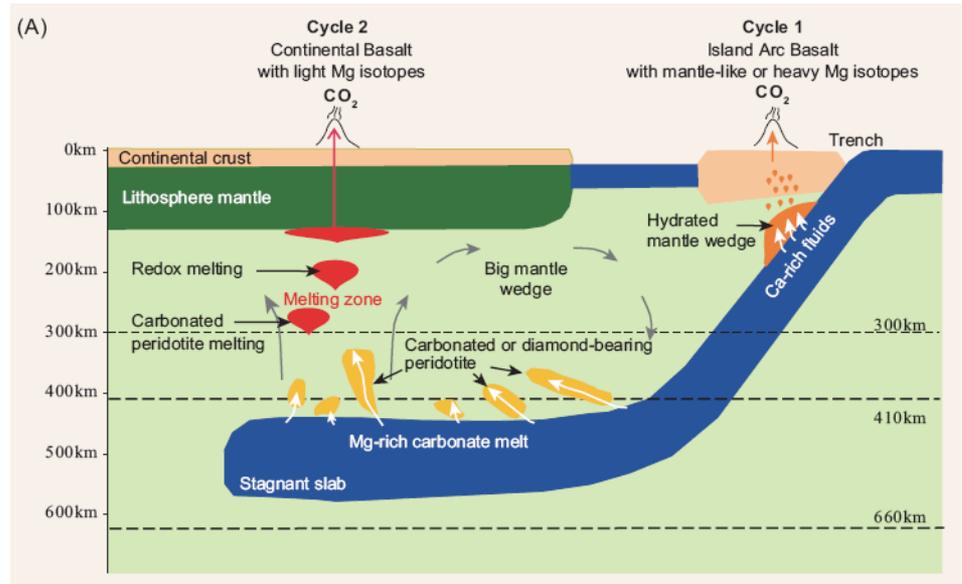
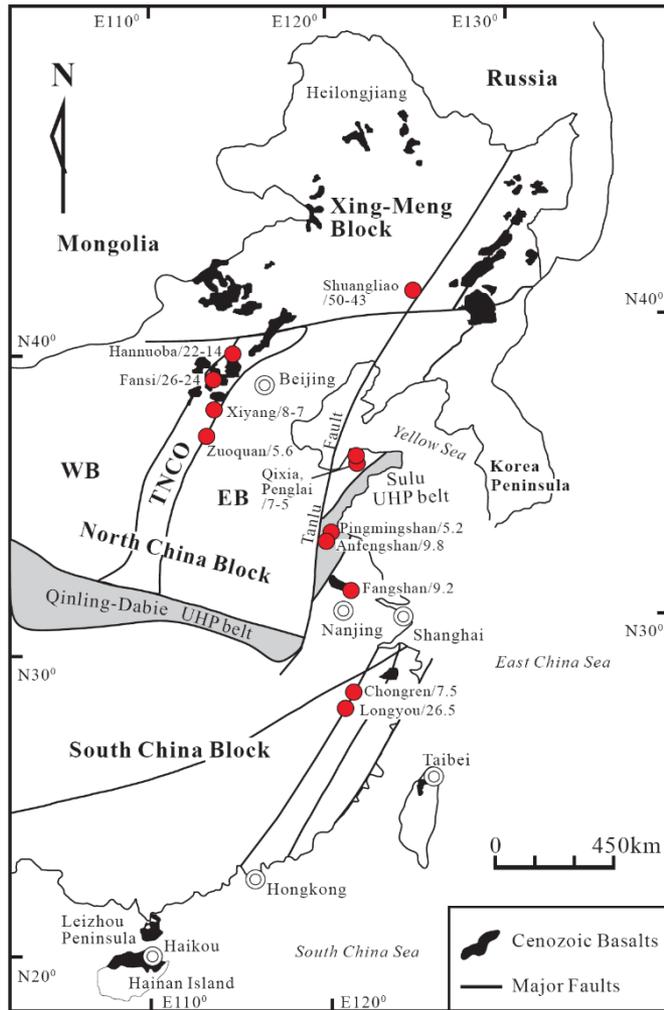
- 氧化态-还原态分离，能产生特征性分馏
- 以橄榄岩熔融为例
- ✓ $D_{\text{Fe}^{3+}} \sim 0.1$; $D_{\text{Fe}^{2+}} \sim 1$



Modified after Dauphas et al, *EPSL* (2014); He et al., *EPSL* (2019)

四、深部氧循环示踪

中国东部玄武岩

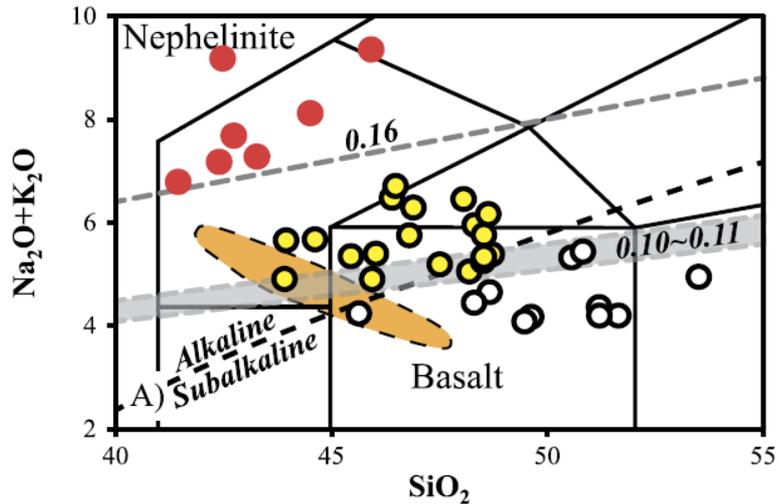


- 大地慢楔
- 显著再循环物质的贡献 (Mg-Zn同位素)
- 研究深部氧循环的理想样品

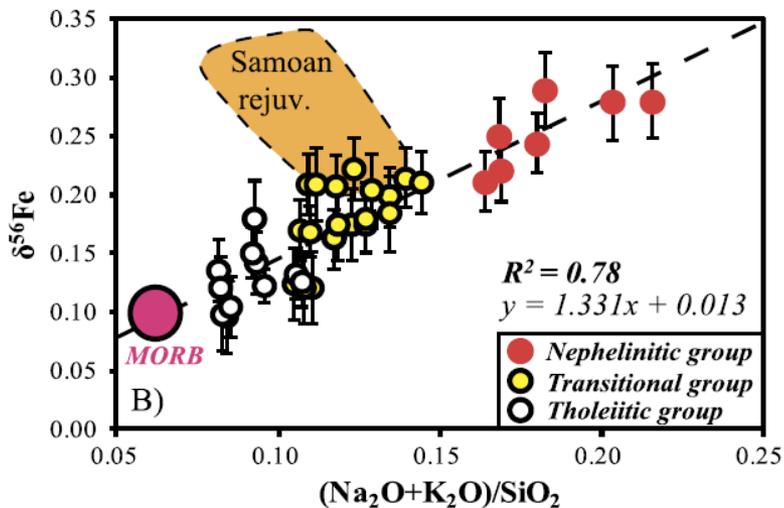
e.g., Liu et al. EPSL (2016); Li et al., NSR (2017)

四、深部氧循环示踪

数据结果

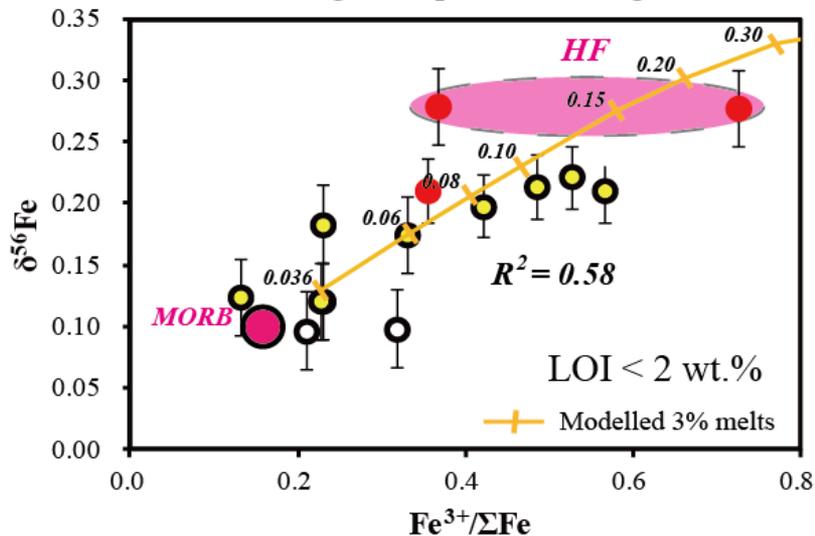
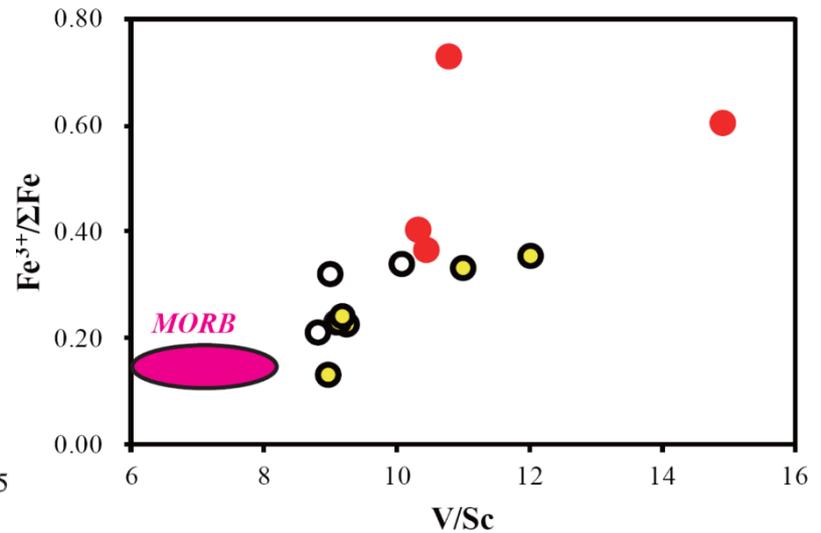
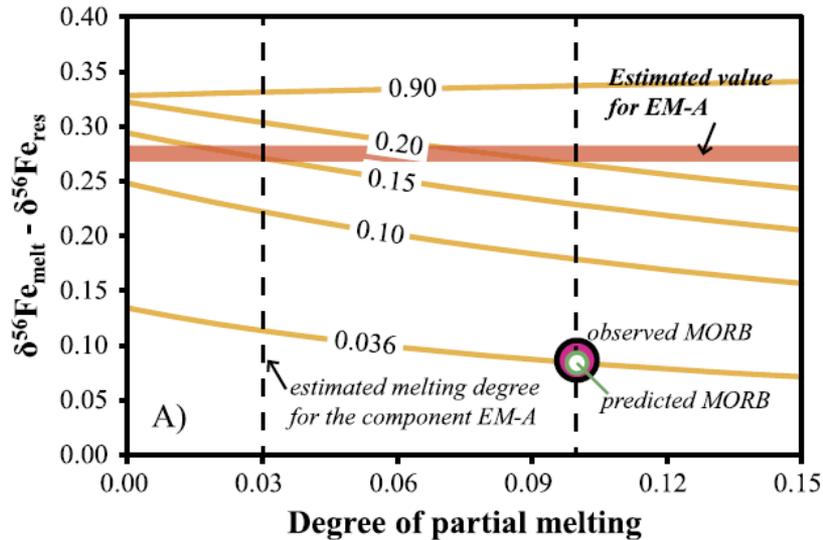


- 中国东部新生代玄武岩普遍具有重铁同位素组成



四、深部氧循环示踪

重铁同位素端元来自氧化性橄榄岩源区熔融



- 定量估计

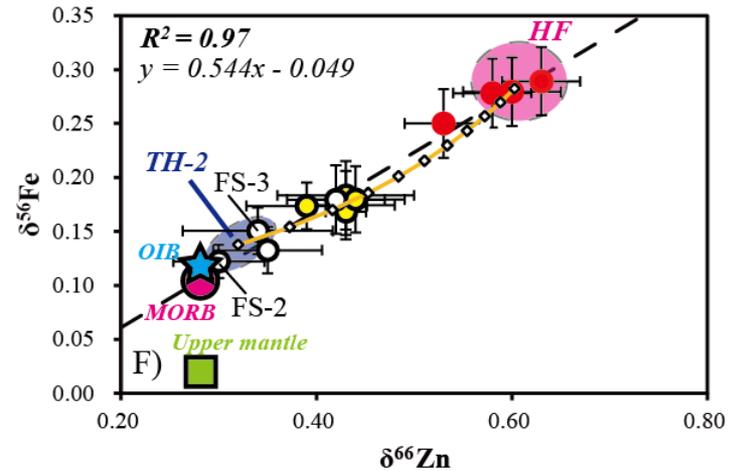
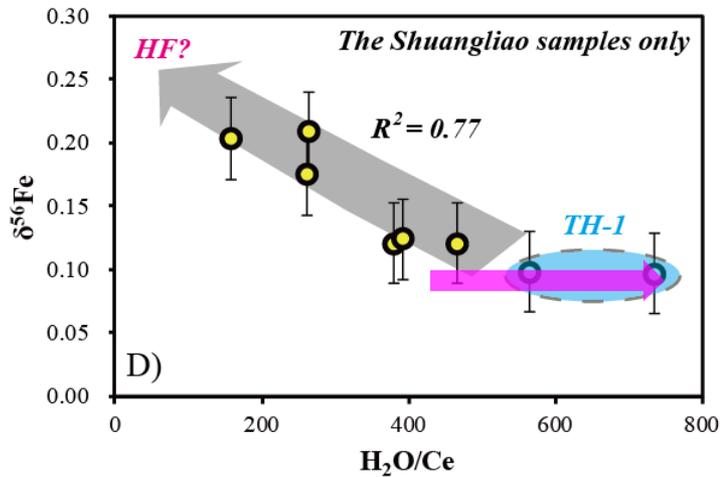
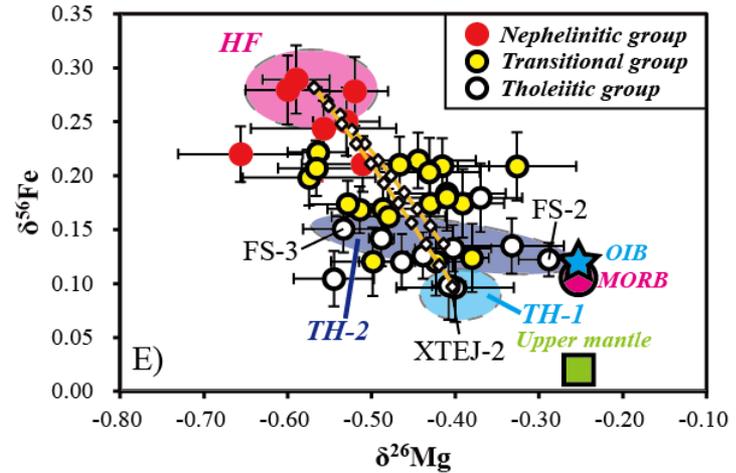
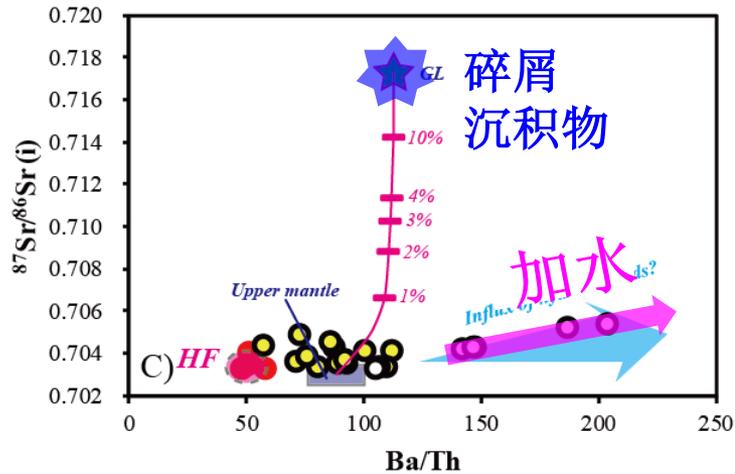
- ✓ 源区 $\text{Fe}^{3+}/\Sigma\text{Fe} \sim 0.15$ (0.036)

- ✓ 母岩浆 $\text{Fe}^{3+}/\Sigma\text{Fe} \sim 0.58$ (0.16)

He et al. EPSL (2019)

四、深部氧循环示踪

源区因再循环碳酸盐交代而氧化



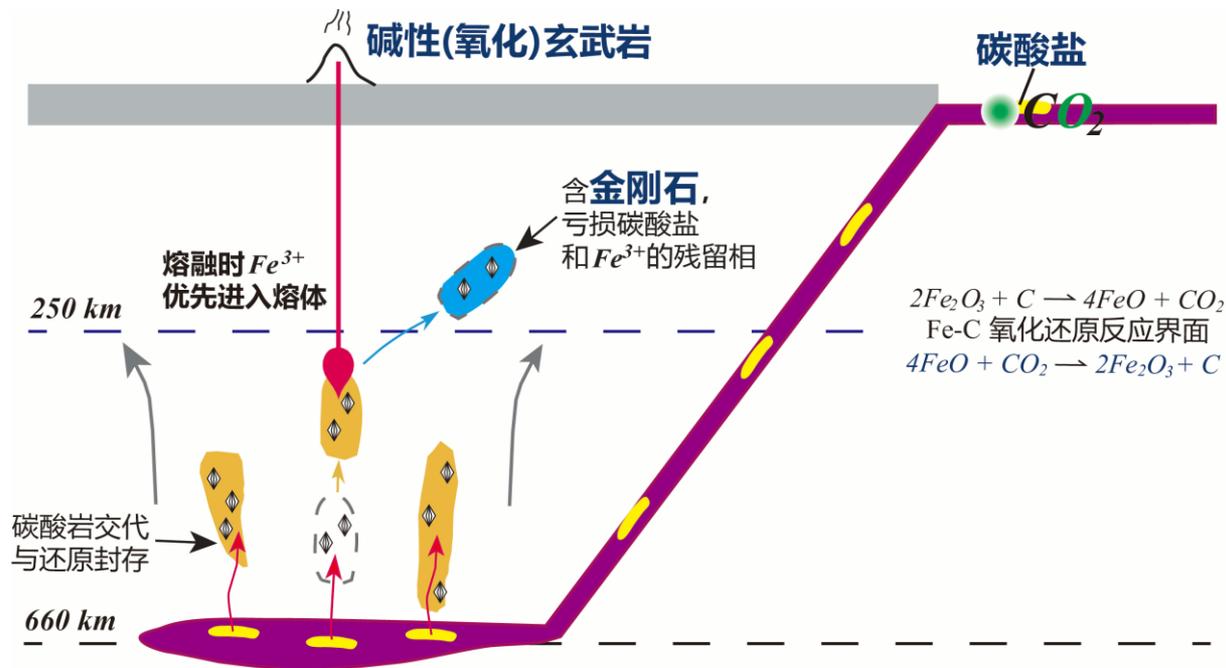
He et al. EPSL (2019)

e.g., Liu et al. EPSL (2016); Li et al., NSR (2017)

四、深部氧循环示踪

深部碳循环驱动的净氧迁移新机制

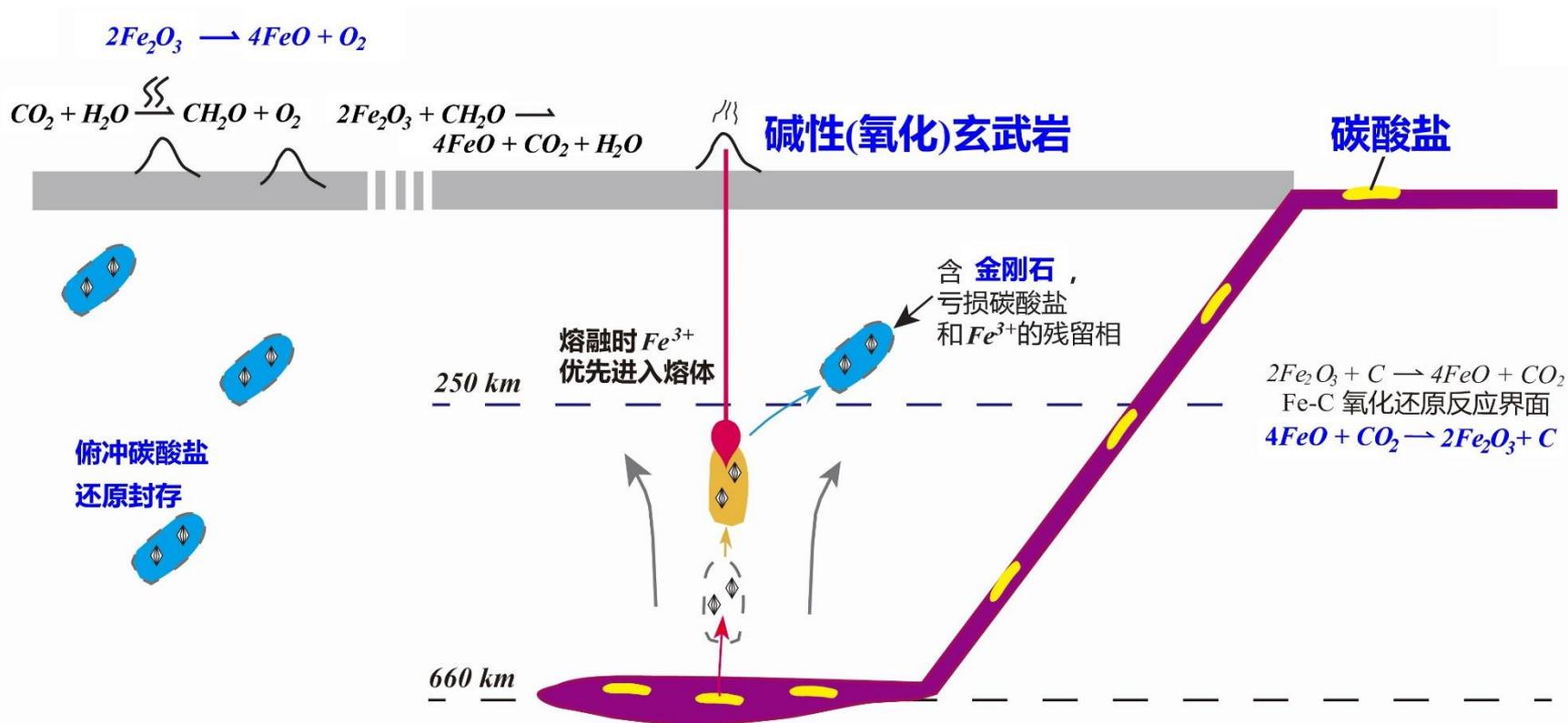
- 地表碳酸盐俯冲进入 > 250 km 的深部地幔；碳酸盐交代产生氧化的地幔(高 $Fe^{3+}/\Sigma Fe$)，自身被还原为金刚石；熔融时氧化剂被优先提取释放到地表：



四、深部氧循环示踪

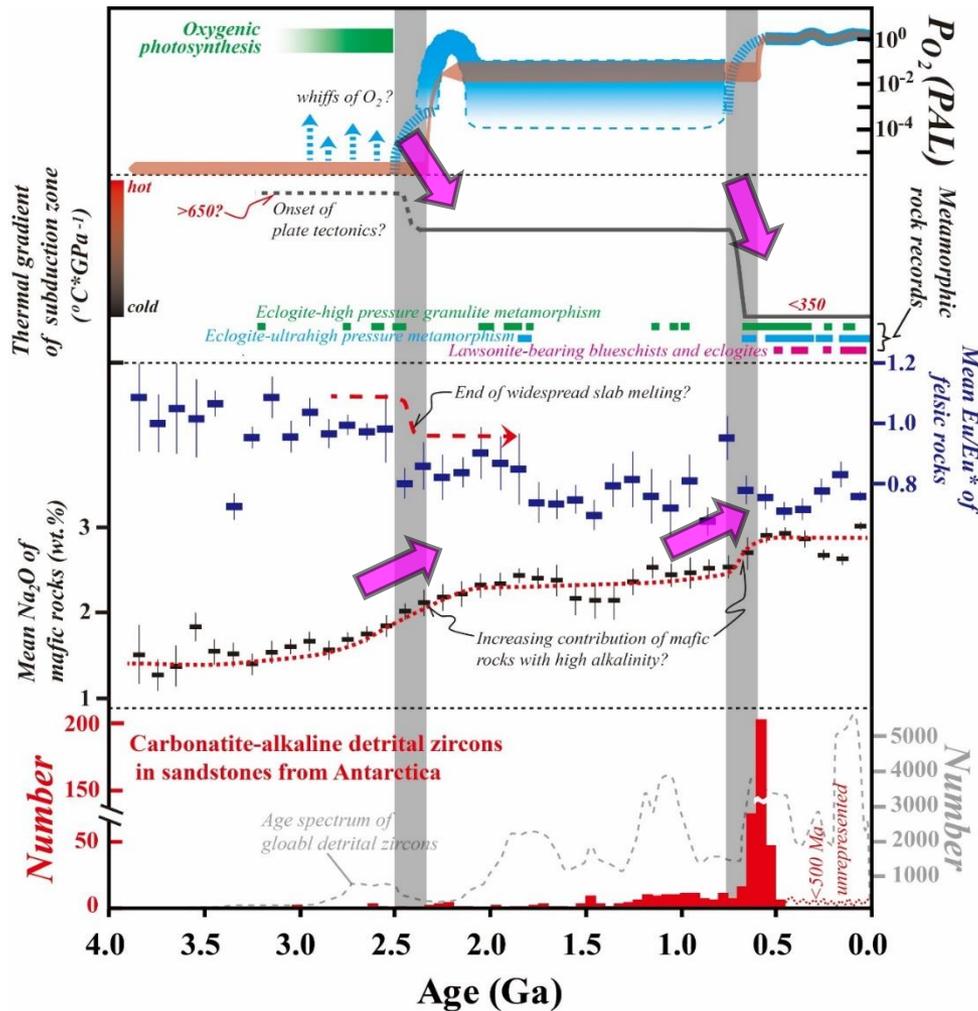
深部氧循环新机制发生的条件

- 碳酸盐深俯冲 (需要冷板块俯冲)
- 相关碱性玄武岩的喷发



四、深部氧循环示踪

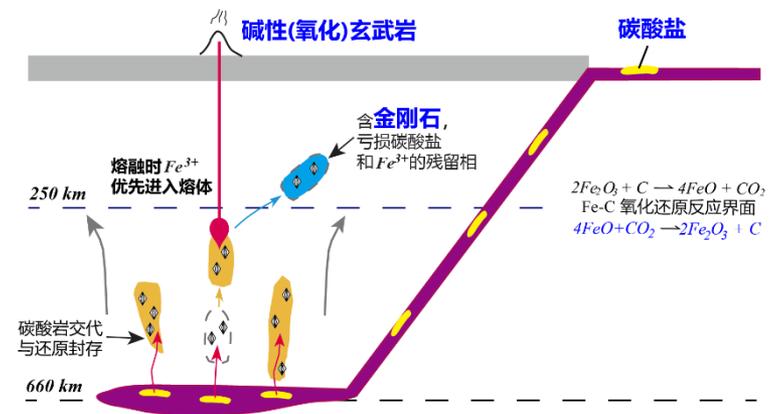
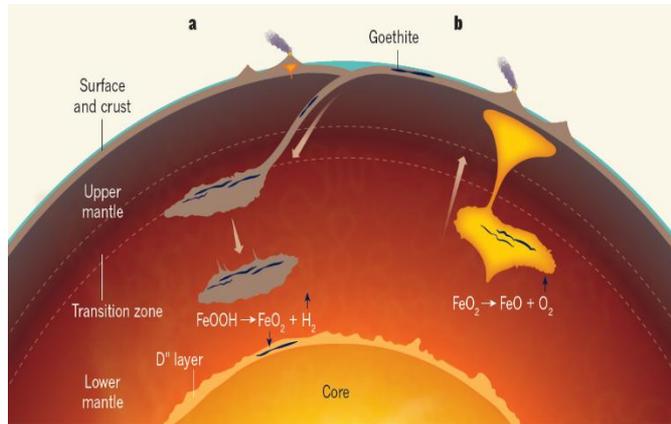
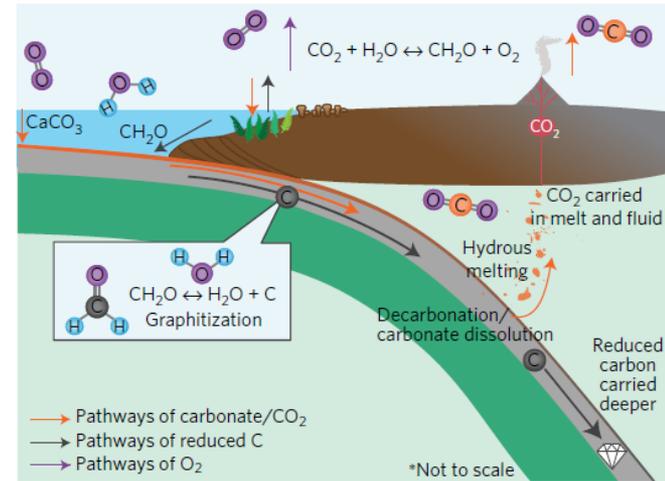
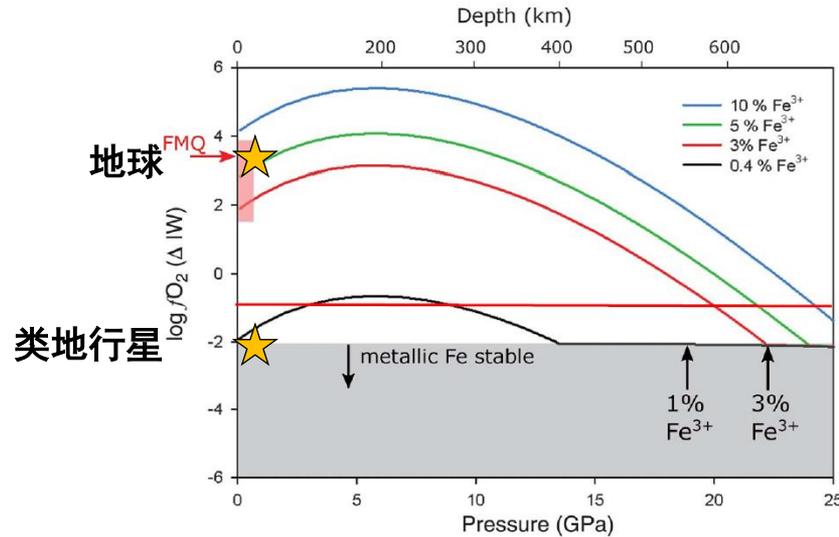
深部氧循环与大气氧升高



- 在GOE和NOE之前:
- ✓ 俯冲带地温梯度两次系统降低
- ✓ 玄武岩碱度两次系统升高，对应碱性岩浆活动加强
- 深部碳循环驱动的氧循环效率升高，应促进了大气氧升高

四、深部氧循环示踪

深部氧循环改变地表氧逸度的几种方式



Hu et al., Nature (2016); Duncan and Dasgupta, NG (2017); Mao et al., NSR (2017); He et al., EPSL (2019); Armstrong et al., Science (2019)

结语

- Fe同位素应用广泛，在示踪地球系统氧循环方面有其独特性
- Fe同位素是示踪地表Fe循环及海洋-大气氧含量变化的重要手段
- 深部氧循环很重要，而Fe同位素示踪提供了潜在的研究手段
- 充满机遇和挑战

致谢!

谢谢聆听，请批评指正!

欢迎报考研究生

